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Influence of Ventilation on Indoor Radon Level

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Detailed radon measurements were conducted at different residential units in Hong Kong in winter time when air-conditioners were off and also in summer time when air-conditioners were on. Ventilation rates were measured concurrently to investigate the influence of ventilation on indoor radon level. The ratio of indoor radon level to outdoor radon level was plotted against ventilation rate, and it was found that a critical value existed after which the indoor radon level could be considered identical to the outdoor level. This result is important for use in ventilation design to reduce indoor radon pollution. © 1997 *Published by Elsevier Science Ltd.*

NOMENCLATURE

A_j	surface area of building material j in the room [m^2]
$ACH = q/V$	air exchange rate of the sampling room [h^{-1}]
C	indoor radon concentration [Bq m^{-3}]
$C(\infty)$	equilibrium indoor radon concentration [Bq m^{-3}]
C_i	initial indoor radon concentration [Bq m^{-3}]
C_o	outdoor radon concentration [Bq m^{-3}]
E_j	radon emanation rate of building material j [Bq m^{-2} h^{-1}]
M_i	initial slope of the radon growth curve inside the sampling room [Bq m^{-3} h^{-1}]
q	leakage rate [m^3 h^{-1}]
t	time unit [h]
V	effective volume of the sampling room [m^3]
λ	radon-222 decay constant (7.553585×10^{-3}) [h^{-1}]

INTRODUCTION

Most buildings in Hong Kong are high rise structures and many residential units are located at high elevation from the ground; soil re-entry of radon gas is a relatively small contribution to the indoor radon level. Granite and concrete are widely used as building materials in Hong Kong, and the radon emanation rate has been found to be high in these materials. The radon emanation rate of concrete has been found to be 21×10^{-6} Bq kg^{-1} s^{-1}, and that of brick is 13×10^{-6} Bq kg^{-1} s^{-1} [1]. The radon emanation rates of these building materials in other countries are much smaller [1]. The indoor radon build up comes mainly from radon emission from building materials, which is different from the situation in the United States and other European countries [2].

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In Hong Kong, the winter period is from mid November to the end of April of the following year. The average temperature is around 25°C in October and falls down to around 16°C in February. In summer time most residential units turn on their air-conditioning units, but in winter time the air-conditioners are usually off. Natural ventilation is thus the common mode for fresh air exchange in winter time. Most people close the doors and windows of their homes in winter time for the purpose of thermal comfort and also for security. The ventilation rate is thus reduced. However, it also depends on how tight the building is and how high the wind speed is around the building. For those buildings with low fresh air exchange, indoor radon can easily accumulate to a high level.

A series of measurement has been conducted to investigate how the fresh air exchange affects the indoor radon level. Particular attention has been paid to the difference between the indoor radon level and the outdoor radon level in different areas.

In this study, 12 residential premises were visited during the period 12 January 1996 to 15 August 1996. The geological composition of the selected sites covered granite, volcanic rocks and reclamation. Three of the sites were located at three outlying islands of Hong Kong. Their geological composition was composed of mainly volcanic rocks. The other sampling sites sat mainly on granite substrates, except for one site which sat on a reclamation substrate composed of granite, rocks and sand. The outdoor radon level was affected by meteorological, topographical and geological conditions. Volumes of the sites varied from 11.3 to 376.1 m^3 and the total radon emitting surface areas varied from 30.5 to 571.4 m^2. Ratios of the radon emitting surface area to volume of the site varied from 2 to 3 m^2 m^{-3}. Table 1 summarizes the location, topography, orientation, meteorological condition and types of building materials and finishing in the sites. The smallest site (with volume 11.3 m^3) was part of a refurnished apartment with wall

Table 1. Information on the sites

Site number and orientation	Topography	Building age (year)	Floor area (m^2)	Volume (m^3)	Meteorological conditions	Finishing materials	Ventilati characteris
Site 1, 15th floor, SW	Near hillside	14	23.5	56.3	Sunny day	Concrete wall with plaster and paint, tiled floor	Air-conditior off, natural ventilation
Site 2, 13th floor, SW	Urban area	0.5	46.5	116.1	Sunny and moderate wind speed	Concrete wall with plaster and paint, wooden floor	Air-conditior off, natural ventilation
Site 3, 10th floor, E	Peak	15	4.5	11.3	Sunny and strong wind speed	Concrete wall with plaster and paint, plastic floor	Air-conditior off, natural ventilation
Site 4, 3rd floor, W	Peak, very near seaside	0.5	92.9	241.5	Sunny and moderate wind speed	Brick wall with plaster and paint, tiled floor	Air-conditior off, natural ventilation
Site 5, ground floor, NE	Hillside (base), quite far from seaside	5	74.3	178.3	Sunny and moderate wind speed	Concrete wall with plaster and paint, tiled floor	Air-conditior off, natural ventilation
Site 6, ground floor, S	Hillside (base) and near seaside	5	74.3	170.9	Raining and moderate wind speed	Brick wall with plaster and paint, tiled floor	Air-conditior off, natural ventilation
Site 7, ground floor, W	Suburban area (near seaside)	8	83.6	209.0	Raining, cloudy and moderate wind speed	Concrete wall with plaster and paint, wooden floor	Air-condition off, natural ventilation
Site 8, 12th floor, N	Rounded by small hill	12	46.5	116.3	Raining, cloudy and moderate wind speed	Wallpaper, wooden floor	Air-condition off, natural ventilation
Site 9, 4th floor	Urban area, new construction	0.5	7.8	19.9	Cloudy and moderate wind speed	Bare concrete	Window type air-condition
Site 10, 10th floor	Urban area, new construction	0.5	7.8	19.9	Cloudy and moderate wind speed	Bare concrete	Window type air-condition
Site 11, 12th floor, S	Hillside	3	116.1	301.8	Cloudy and moderate wind speed	Plaster wall, wooden floor	Split unit air-conditione
Site 12, three-storey house, N	Hillside	3	144.7	376.1	Cloudy and moderate wind speed	Plaster wall, wooden floor	Split unit air-conditione

partitions separating it from the rest of the unit. It could be treated as separate premises in our test.

EXPERIMENTAL METHOD

A solid state radon detector, Niton Rad7, 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 α radiation directly to an electrical signal using the alpha spectrometry technique which is able to distinguish radon from thoron and signal from noise [3]. The detector is sent back to the manufacturer for calibration twice every year. The calibration procedure is carried out in a well-controlled environmental chamber and the reading is compared to a master instrument. Overall calibration accuracy of the detector is 5% based on a sensitivity of 0.4 counts min^{-1} pCi^{-1} l^{-1}. The range of the monitor is from 0.1 to 5000 pCi l^{-1}.

For sites 1–10, two Rad7 detectors were used for continuous monitoring of both the indoor and outdoor radon levels. One detector was located in either the living room or the bedroom depending on which room was closer to the center of the unit. The sampling inlet was located at breathing zone level. The other detecto connected with a flexible sampling tube to collec outdoor fresh air for background measurement. The door radon level was measured simultaneously wit indoor level. The sampling flow rates of the dete were preset at 1 l min^{-1}. The measurement in each lasted for about 3 days (72 h). For sites 1–8 the tests conducted in winter and all the air-conditioners switched off. For sites 9 and 10 the tests were do summer and the window air-conditioner units were

Site 11 had a larger area and three tests were cond at the site. There was a living room, a dining room four bedrooms in the premises. Split unit air-conditi were used in the premises. Radon measurements conducted in the living room and the four bedr simultaneously. The outdoor radon level was also n tored concurrently.

Site 12 was a three-storey house and three tests conducted on this site. The house had one living together with two to three bedrooms on each floo basement was attached to the underground car Split unit air-conditioners were provided on each except for the basement. In test 1 all the internal d were open and all the air-conditioning units in the h were turned on. Radon measurements were conduct the basement area, ground floor living room and se floor living room. The measurement also lasted for 72 h. The outdoor radon level was monitored by one detector concurrently. In test 2 all the internal doors were open and all the air-conditioning units were turned off. Radon measurements were conducted at the ground floor living room, first floor living room and second floor living room, also for 72 h. The outdoor radon level was also monitored continuously. In test 3 all the doors and windows of the house were opened for 1 h and then all the openings were closed. No air-conditioning was on during this period of measurement.

The air exchange rate of each site was determined by the tracer gas decay method. CO_2 was used as the tracer gas in the study and a Telaire-1050 monitor was used. The Telaire 1050 model uses non-dispersive infrared (NDIR) for CO_2 measurement in diffusion gas sampling mode. The accuracy is 5% of the reading or 50 ppm depending on which is larger. The maximum CO_2 level that can be detected is 2000 ppm. The initial CO_2 concentration was built up to around 2000 ppm and was allowed to decay freely to the background level. The ambient CO_2 level was also measured and found to be between 400 and 500 ppm depending on the location of the site. Calibration of the monitor was done regularly in the laboratory using a low pressure gas bottle containing 17 l of calibrated CO_2 gas in nitrogen. The dosing level at 2000 ppm at each site has been found to be acceptable within our testing condition since the decay took about 1 h and a fairly clear straight line was found in the logarithm plot. The fresh air exchange rate was calculated from the CO_2 decay curve. During the CO_2 measurement period no occupant was staying inside the unit. One day time ventilation rate and one night time ventilation rate were measured for sites 1–8. For sites 9–12 only the day time ventilation rates were measured. Other than the radon and air exchange rate measurements, parameters like temperature, size of the residential units, building materials used, site orientation, topographic and meteorological conditions were also recorded in the experiment.

RESULTS AND DISCUSSION

Measurement results at sites 1–10

The mean indoor and outdoor radon concentrations during the 72 h period are summarized in Table 2. Examples of some of the radon measurements are shown in Figs 1–4.

The highest mean indoor radon level recorded was 424 Bq m^{-3} at site 6 on the ground floor. During the experiment, the occupant was not present. The doors and windows were closed. Under low air exchange rate condition, radon could accumulate up to a very high level within 1 day. The radon growth curve is shown in Fig. 3. At this site the indoor radon level was six times higher than the outdoor radon concentration (71 Bq m^{-3}). It was also two times higher than the guideline set by the Hong Kong Environmental Protection Department (200 Bq m^{-3}). The outdoor radon level was found to be very high due to the geological nature of the soil in that area. The house sits on a granitic area where the radium content has been found to be high. In addition, the wind movement was quite stagnant on the date of measurement and the convective effect in removing ground floor pollutant was poor. This explained why the outdoor level was high on that day (similarly for sites 9 and 10). Site 6 was not equipped with an air-conditioning unit and the windows were all closed during the measurement which followed the living pattern as indicated by the occupants. High outdoor radon level and low ventilation rate led to a very high indoor radon accumulation at the site.

The minimum indoor radon level was observed at site 2 on the 13th floor. The indoor radon level was 15 Bq m^{-3} which was almost identical with the outdoor radon level (14 Bq m^{-3}).

For those measurements conducted in winter time (sites 1–8), all the windows were closed except one which was left partially closed. For the measurements conducted in summer time (sites 9 and 10), all the windows were closed and the air-conditioning units were turned on. The average air exchange rates in each site are also summarized in Table 2. The air exchange rate varied from 0.20 h^{-1} at site 6 to 7.2 h^{-1} at site 3. In winter when the air-conditioners were off, outdoor air exchanges with indoor air by two mechanisms. One is diffusion and the other is convection. In general, diffusion is negligible when compared with convection. The air exchange rate depends on the tightness of the building, the window opening condition and also the outside wind condition. If the outside wind speed is high, a higher pressure differential is established across the outside and inside. In this case, a higher air exchange rate is expected. From Tables 1 and 2, it is observed that those sites located at a higher

Table 2. Average indoor and outdoor radon levels and ACH at sites 1–10

Location	Day time ACH (h^{-1})	Night time ACH (h^{-1})	Indoor R_n (Bq m^{-3})	Outdoor R_n (Bq m^{-3})	$(R_n)_{in}/(R_n)_{out}$
Site 1	4.0	2.9	20	16	1.25
Site 2	2.9	3.6	15	14	1.07
Site 3	5.4	9.0	28	20	1.40
Site 4	1.4	1.4	31	13	2.38
Site 5	0.4	0.2	108	20	5.40
Site 6	0.2	0.2	424	71	5.97
Site 7	0.5	0.3	137	14	9.79
Site 8	2.2	1.1	62	27	2.30
Site 9	1.2	—	179	59	3.03
Site 10	0.4	—	219	45	4.87

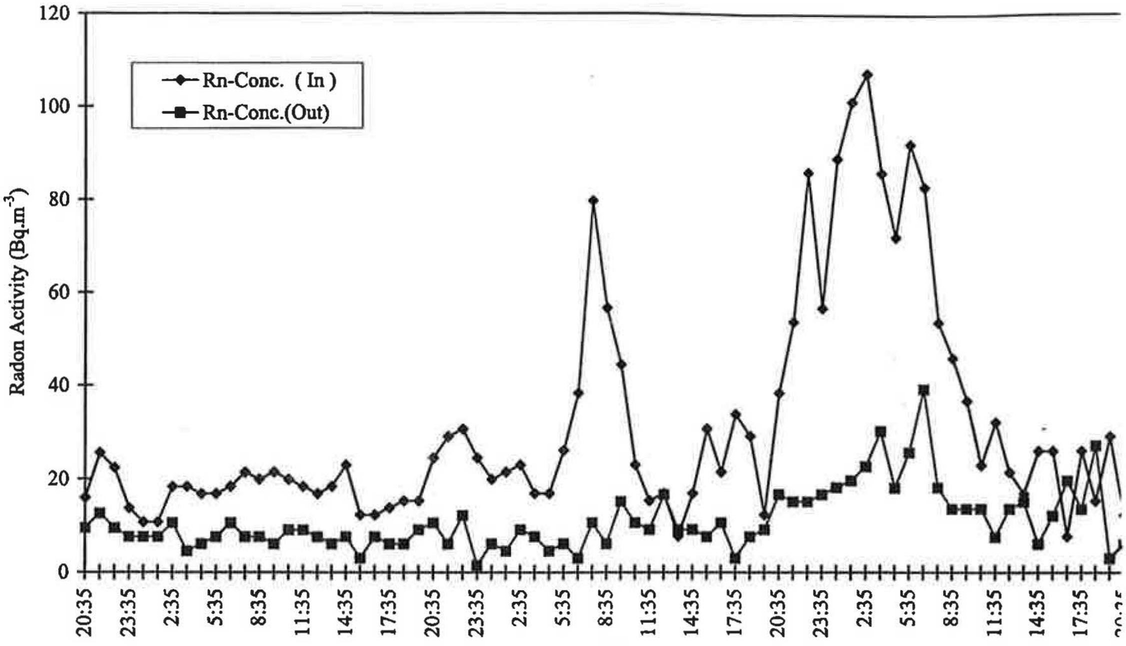

Fig. 1. Indoor and outdoor radon level in the residential site 3.

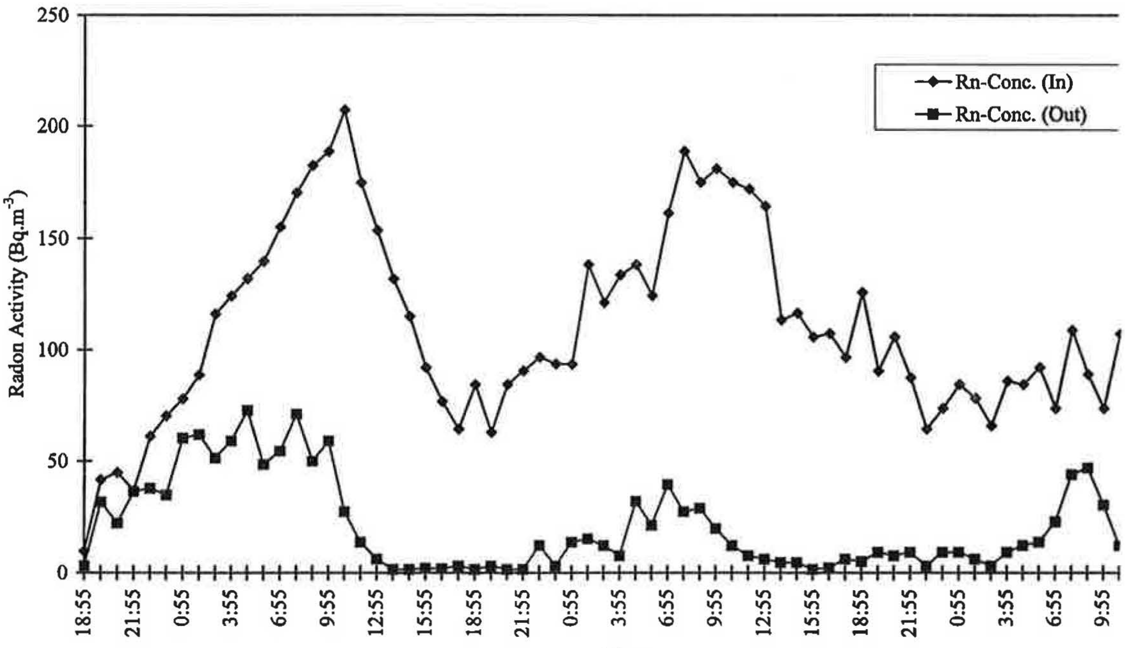

Fig. 2. Indoor and outdoor radon level in the residential site 5.

elevation have in general higher air exchange rates (from 3.25 to 7.20 h^{-1}). In summer the fresh air was supplied mainly by mechanical ventilation and the amount depended on the capacity of the air-conditioning unit.

The high air exchange at some sites was probably due to wind condition. It was noticed that very strong wind movement was observed at site 3 since it was located on top of a hill and the unit was on the 10th floor. The ratios of indoor to outdoor radon levels were close to unity at site 1, site 2 and site 3 where high air exchange rates were found. The strong mixing of outdoor air with indoor air has made the indoor radon level very close to the outdoor radon level. The two sites having median air ex rates (1.40 h^{-1} at site 4 and 1.65 h^{-1} at site 8) ha of indoor to outdoor radon levels around 2.4. Th sites with very low air exchange rates (0.20 to 0. had been found to have very high ratio of in outdoor radon levels (5 to 10).

From Table 2 it is noticed that outdoor rado varied from 13 to 27 Bq m^{-3} at seven sites and o 6 showed a very high outdoor radon level. Tl probably due to the geographical composition area. Since the indoor radon accumulates to a ve level if the air exchange rate is low, a higher rad

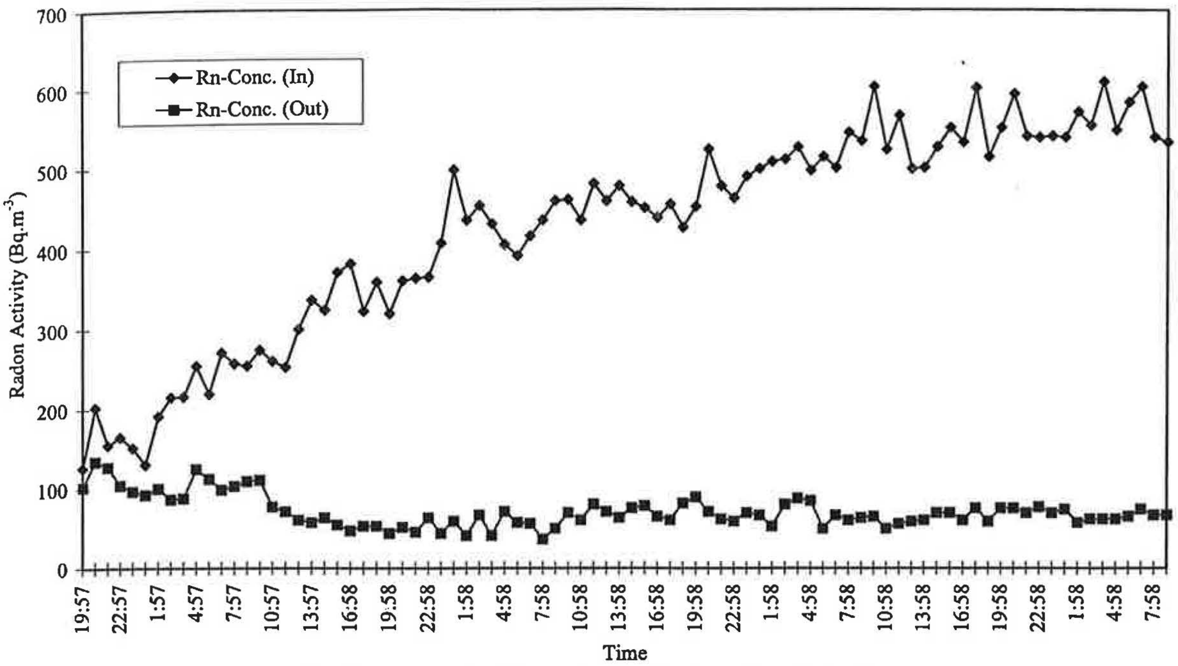

Fig. 3. Indoor and outdoor radon level in the residential site 6.

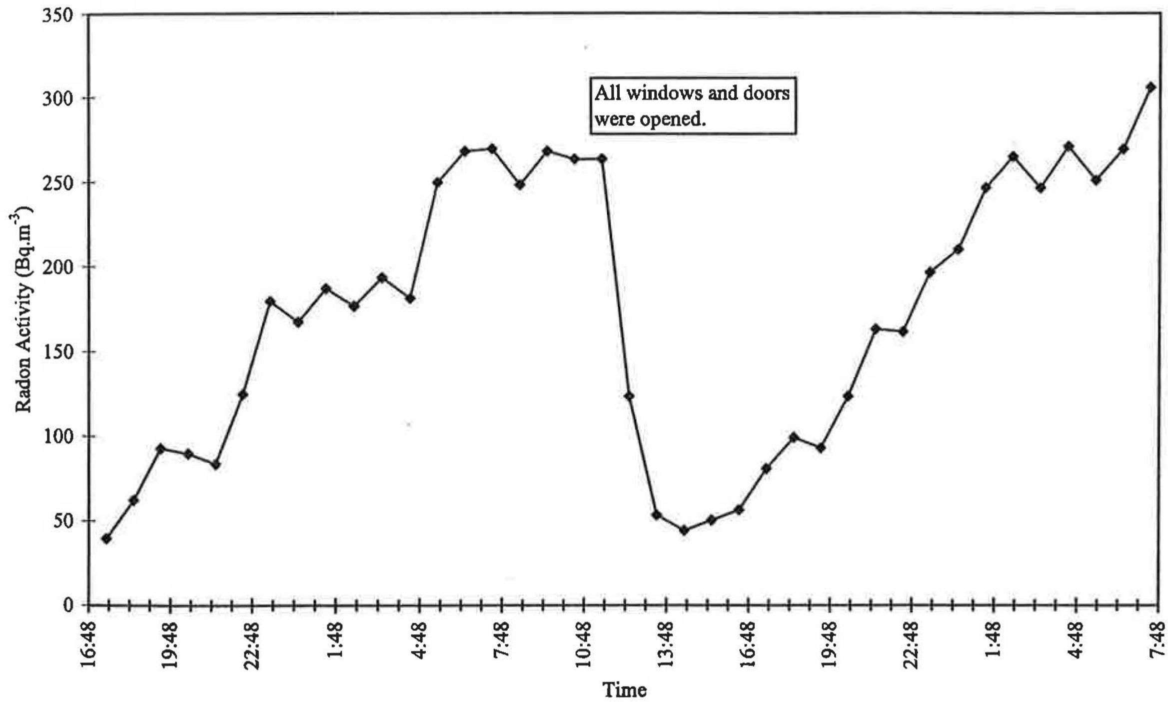

Fig. 4. Indoor radon level in the residential site 12.

can be expected in those tight buildings in winter when most windows are closed. The same situation can be found in some suburban areas with the residential units located close to the ground floor since most of the windows are closed in order to keep mosquitos or other insects away from the house.

Diurnal variations of both outdoor and indoor radon concentrations have been observed at some sites. The results obtained at site 3 and site 5 (shown in Fig. 1 and 2, respectively) are used to illustrate this point. The outdoor radon level peaked at dawn or early in the morning and dropped to the lowest level in the afternoon. Diurnal variations are believed to be directly associated with atmospheric stability [4]. The atmosphere is usually very stable early in the morning due to the temperature inversion effect [5]. Outdoor radon comes mainly from soil and high radon concentration is expected at ground level. The very stable atmospheric layer in the morning hinders the radon gas from moving away into the upper layer. As sunlight heats up the ground, the actual temperature lapse rate in the air is larger than the dry adiabatic lapse rate of an air parcel, and thus the temperature

Table 3. Measurement result at site 11

Test number	Test conditions	Air exchange rate (h^{-1})	Indoor R_n ($Bq\,m^{-3}$)	Outdoor R_n ($Bq\,m^{-3}$)	$(R_n)_{in}/(R$
Test 1	All internal doors open/air-conditioning on	0.41	193	5.3	36.5
Test 2	All internal doors open/air-conditioning off	0.49	176	5.3	33.2
Test 3	All internal doors closed/air-conditioning on	0.22	246	5.3	46.5

inversion layer is destroyed. The atmospheric layer becomes unstable and the near-ground radon gas is diluted to the upper atmosphere. The outdoor radon level will decline until the radiant cooling of the surface stabilizes the atmosphere and afterwards the temperature inversion will be established.

In Fig. 2, the indoor radon level followed the outdoor trend. A time lag of about 1 h was noticed, and it has been seen in other site measurements that the time lag was reduced when the air exchange rate was higher. The measurement is similar to tests conducted by other researchers [6].

Measurement results at site 11

Three tests were conducted at site 11 and the results are presented in Table 3. The purpose of the tests was to investigate how the ventilation and internal door opening affected the indoor radon level. The air exchange rates were relatively low since split air-conditioning units were used in the premises. All the windows were closed in the experiment, which simulated real life practice in the premises. There was no fresh air supply in the split units and the fresh air exchange was by means of infiltration through the building fabric and gaps underneath the main door.

It was observed that with the air-conditioners on or off the ventilation rates were almost the same (comparing test 1 and 2) despite a small difference which might come from experimental error. The result showed that internal circulation had no influence on the ventilation rate. The result in test 3 is interesting since it was observed that with all the internal doors closed the mean air exchange rate was much lower than that in the other cases. Meteorological conditions during the two tests were observed to be quite similar, even when no measurement was conducted. Circulation of internal air basically shows no influence on the fresh air supply rate due to mechanical ventilation, but it will affect the infiltration component. Closing of internal doors may block the infiltr movement from one side of the premises to th depending on the layout and wind charact However, detailed measurement of meteorologic ditions was required since influences of indoor a door temperature difference, wind speed, etc. w important.

The ratio of the indoor radon to outdoor rad was found to be very high in all cases, from 33.2

Measurement results at site 12

Three tests were conducted at site 12 to illustr change of indoor radon level with elevation and t how the indoor radon level was reduced when th and windows were fully open. The results are sh Table 4. In tests 1 and 2, all windows were closed the experiments, which again simulated the living of the occupants. Similar to the results at site ventilation rates were low since split unit air-condi were used.

In test 3, all doors and windows were closed beginning and then all fully opened for 1 h. At th time, a trace gas experiment was performed to m the air exchange rate at the moment. In extrem tilation conditions, the radon accumulation pheno and purging effect are shown in Fig. 4. The indoor level could be reduced to the outdoor level under ventilation conditions. However, the indoor radon also easily accumulate to a very high level in poc tilation conditions, just as at site 6.

Entirely opposite results for the indoor rado were observed in test 1 when air-conditioning unit on and in test 2 when all air-conditioning units w (see Table 4). In test 1 the indoor radon level dec with elevation, while in test 2 it increased with ele In test 1 the radon level was the highest in the bas since there was no air-conditioning unit installed and the radon emanation was strong from the co

Table 4. Measurement result at site 12

Test number	Test conditions	Air exchange rate (h^{-1})	Indoor R_n ($Bq\,m^{-3}$)	Outdoor R_n ($Bq\,m^{-3}$)	$(R_n)_{in}$
Test 1	All internal doors open/air-conditioning on	0.72	2/F: 115; G/F: 13; basement: 147	50	2
Test 2	All internal doors open/air-conditioning off	0.40	2/F: 244; 1/F: 240; G/F: 122	50	4
Test 3	All doors and windows fully opened for 1 h and closed again	0.4 (closed case)	2/F: 245 (mean level considered within 2:27–11:27)	45	5
			9.9 (all openings open)	2/F: 49 (mean level considered within 12:27–14:27)	1

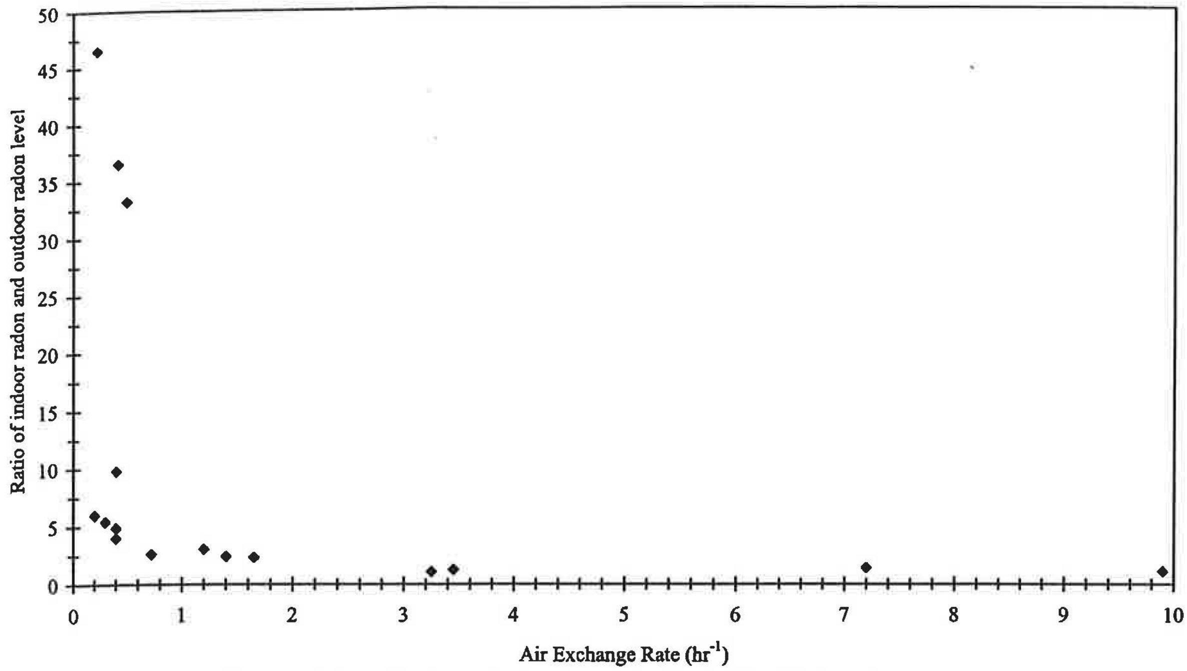

Fig. 5. Variation of indoor radon/outdoor radon level ratio with air exchange rate.

base. The air circulation was better at higher floors since air-conditioning units were on. In test 2 the indoor temperature (32.3°C) on the day was slightly higher than the outdoor temperature (31.3°C) and the stack effect brought radon accumulation to the top floor.

Critical ventilation rate for radon mitigation

The ratio of indoor to outdoor radon level from Tables 1–4 was plotted against the air exchange rate and the result is presented in Fig. 5. A very clear curve is observed and the ratio decreased with air exchange rate. At all the sites the effect of radon emanation from building materials varied, but the difference might be small when compared with the effect of ventilation. The variation of radon level with air exchange rate can be illustrated by the following equation:

$$\frac{dC}{dt} = -\lambda C + \frac{\sum E_j A_j}{V} + \frac{q(C_o - C)}{V}, \tag{1}$$

$$C = \left(C_i - \frac{\sum E_j A_j + qC_o}{V\left(\lambda + \frac{q}{V}\right)} \right) e^{-(\lambda + (q/V))t} + \frac{\sum E_j A_j + qC_o}{V\left(\lambda + \frac{q}{V}\right)}. \tag{2}$$

Since $\lambda \ll q/V$, the steady state solution becomes

$$C(\infty) = C_o + \frac{\sum E_j A_j}{q}. \tag{3}$$

In equation (3) it can be seen that if a building is under strong ventilation condition, the indoor radon level is approximately the same as the outdoor radon level. The emission term $\sum E_j A_j$ can be shown to be related to the initial radon growth curve at the premises if C_i is assumed to be close to C_o.

Differentiating equation (2) with respect to time and taking t to approach zero, the following equation is found:

$$M_i = \left.\frac{dC}{dt}\right|_{t \to 0} = \frac{\sum E_j A_j}{V}. \tag{4}$$

Then

$$\sum E_j A_j = M_i V. \tag{5}$$

equation (5) was substituted into equation (3):

$$C(\infty) = C_o + \frac{M_i V}{q}$$

or

$$\frac{C(\infty)}{C_o} = 1 + \frac{M_i}{C_o(\text{ACH})}. \tag{6}$$

This equation is only valid when the change of ACH over time is small. If the ACH is large enough, the ratio is close to unity as observed in Fig. 5. The problem is that we need to know how large the ACH is in order to satisfy this unity ratio condition. For the sites investigated, M_i varied from 11 to 18 Bq m^{-3} h^{-1} and C_o varied from 13 to 71 Bq m^{-3}. M_i was estimated in separate tests where the windows were opened at the beginning to allow thorough mixing of indoor air and outdoor air so that $C_o = C_i$, and then the windows were closed to allow for radon growth inside the room. The purpose of these separate tests was to find the radon emanation rates of the materials in the rooms. M_i represents the initial slope of the radon growth curve at each site in the separate tests. The graphs for the radon growth are not shown in this paper. Based on these conditions, if ACH is larger than 3 h^{-1}, and taking the mean values of ACH and M_i in the ranges given, the indoor radon to outdoor radon ratio is only 10% higher than unity.

In Fig. 5 it is observed that a critical ventilation rate exists after which the indoor radon level is close to the outdoor radon level. The observation agrees with equation (6). The critical ventilation rate for this group of buildings was found to be around $3\,h^{-1}$. The exact value depends on the building envelope design and building materials used in the interior, as well as other corridor flow patterns, etc. However, the concept seems to be useful as the building services engineer may develop a rule of thumb based on the result by picking up a certain ventilation limit so that radon mitigation can be carried out effectively. The ventilation rate has been shown to be an important factor in reducing indoor radon level, not only from the result of this study, but also from other research work [7]. As the outdoor radon level indicates the minimum indoor radon level that the premises can sustain, the critical ventilation rate shown in this study provides a preliminary guideline so that the minimum indoor radon level can be achieved if the ventilation rate is kept above the critical value. Future research work is being conducted to expand the database so that a more accurate critical ventilation rate can be defined.

CONCLUSION

This paper reports indoor and outdoor radon l 12 residential sites in Hong Kong. Large variation exchange rate have been observed at these sites. Th of indoor to outdoor radon level has been found t high as 46.5 when the air exchange rate is around (The indoor radon level was close to the outdoor level when the air exchange rate was higher than Diurnal variation caused by the temperature in effect has been observed in some sites where the level peaked at dawn and reached its lowest valu afternoon. It has been found that the ventilati plays a very important role in controlling indoor concentration. However, the result is incomplete v information on how much the building materia tribute to the indoor radon level. Recently, a small ber has been built in our laboratory and a compre study on the radon emanation rates of different b materials used in Hong Kong is being carried out

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