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Koncentracija radona v prezračevanih notranjih prostorih v Hong Kongu

The Radon Concentration in a ventilated Indoor Space in Hong Kong

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Stopnja zločanja radona je veliko večja za gradbene materiale iz Hong Konga v primerjavi z materiali iz drugih območii. Izpostavljanje visokim stopnjam sevanja radona pomeni resno ogrožanje zdravja. Za namen izpeljave analize notranje koncentracije radona je bilo predpostavljeno, da se ti materiali pojavljajo na tleh, stenah in stropu. Stopnjo notranjega sevanja radona v zraku lahko določimo "ročno" in s simuliranjem dinamike fluida, tako da z različnimi stopnjami izmenjavanja zraka izračunamo vpliv stopnje ventilacije na količino radona notranjega zraka. Rezultati kažejo, da stopnja prezračevanja igra pomembno vlogo pri nadzoru notranje koncentracije radona. Radon v pisarnah v splošnem ni glavni dejavnik pri določanju stopnje prezačevanja, čeprav je priporočljivo obdržati čim nižjo stopnjo le-tega.

(Ključne besede: prezračevanje prostorov, koncentracije radona, materiali gradbeni, analize)

The radon emanation rate has been found to be much higher for building materials from Hong Kong compared with those from other places. Exposure to high radon levels poses a serious health risk. For the purpose of carrying out A worst-case analysis of the indoor radon concentration it was assumed that no finishing materials are applied to the floor, walls and ceiling. The level of indoor radon radiation in the air is studied by hand calculation and Computational Fluid Dynamics simulation using different air exchange rates to evaluate the influence of ventilation rate on the indoor-air radon level. Results show that the ventilation rate plays a very important role in controlling the indoor radon concentration. It is concluded that radon in offices is, in general, not a major factor when considering ventilation rate, although it is always advisable to keep the radon level as low as practically possible.

(Keywords: ventilation, indoor radon concentration, building materials, analysis)

0 UVOD

Večina poslopij v Hong Kongu je visoke konstrukcije, zato delež radona na tleh le malo prispeva k notranji stopnji le-tega. Granit in beton sta zelo uporabljena gradbena materiala v Hong Kongu, v teh materialih pa je stopnja izločanja radona zelo velika. Stopnja izločanja radona betona je 21×10^{-6} $Bqkg^{-1}s^{-1}$ in opeke 13×10^{-6} $Bqkg^{-1}s^{-1}$ [13]. Stopnja izločanja radona teh gradbenih materialov je v drugih območjih dosti nižja [12]. Notranje povečanje količine radona je posledica izločevanja radona iz gradbenih materialov v Hong Kongu, kar se razlikuje od stanja v ZDA in evropskih državah [9].

Skoraj vse pisarne v Hong Kongu so v visokih stavbah in imajo osrednjo klimatizacijo. Veliko od njih ima okna, ki se jih ne da odpreti, kar pomeni, da naravno prezračevanje ni mogoče. Trenutno si inženirji prizadevajo, da bi se izognili pritožbam glede

0 INTRODUCTION

Most buildings in Hong Kong are high-rise structures and so soil re-entry of radon gas has only 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 from these materials has been found to be high. The radon emanation rate from concrete has been found to be 21×10^{-6} $Bqkg^{-1}s^{-1}$ and that of brick is 13×10^{-6} $Bqkg^{-1}s^{-1}$ [13]. The radon emanation rate of similar building materials which come from other places are much lower [12]. The indoor radon build-up comes mainly as a result of radon emission from building materials in Hong Kong, which is different from the situation in the United States and European countries [9].

Almost all the offices in Hong Kong are located in high-rise buildings and adopt central air-conditioning. Many of them only have fixed windows, i.e. no natural ventilation is available. To avoid any indoor-air quality complaints, there is a trend for slabega zraka, postaviti na koncu dovodne odprtine dušilnik, ki bo omogočal stalen dotok, tako da bo največja količina zunanjega zraka vedno vsem na voljo, čeprav je v nasprotju s primarnim ciljem varčevanja energije.

Raziskave radona na širšem območju v notranjih prostorih v letih 1992/93 in 1995/96 je opravil Oddelek za varovanje okolja v Hong Kongu, te so pokazale koncentracijo radona v pisarnah.

Radon je radioaktiven plin brez okusa in vonja. Nastane, ko se radij topi v nekaterih prsteh in kameninah, posebej v granitu, radioaktivno razpada.

Izpostavljanje kombinaciji tobačnega dima in visoki stopnji radona pomeni resno ogrožanje zdravja. Kadilec cigaret ima trikrat večjo možnost obolenja za pljučnim rakom od nekadilca, ki je izpostavljen visoki stopnji radona. Glede na izračune je bilo v Hong Kongu leta 1986 od vseh smrti za pljučnim rakom 13% tistih, ki jih je povzročil radon.

Nivo radona je bil najvišji v Hong Kongu v primerjavi z drugimi mesti po svetu [4]. Povprečna koncentracija radona v pisarnah, tovarnah, šolah, javnih mestih in bolnišnicah je bila 77 Bq/m^3, 76 Bq/m^3, 43 Bq/m^3, 64 Bq/m^3 in 55 Bq/m^3 [12]. Izračuni nedavnih raziskav so pokazali, da je samo 5,1 % javnih mest preseglo 200 Bq/m^3 ([4] do [6]). Priporočena stopnja koncentracije notranjih prostorov v ZDA je 150 Bq/m^3 [2].

engineers to put a constant-flow damper at the intake end so that the maximum amount of outdoor air is always provided to the occupied area, although this defeats the prime objective of energy saving.

Territory-wide indoor radon surveys were conducted by the Hong Kong Environmental Protection Department in 1992/93 and 1995/96. The indoor radon concentration in Hong Kong offices was found.

Radon is a radioactive gas with no taste, smell nor odour. It is formed when radium found in most soils and rocks, particularly granite, disintegrates radioactively.

Exposure to a combination of tobacco smoke and high radon levels poses a serious health risk. A cigarette smoker runs three-times greater risk of getting lung cancer than non-smokers exposed to high radon levels. According to a relative risk model, the calculated number of radon-induced lung-cancer deaths in Hong Kong in 1986 was about 13% of the total number of lung-cancer deaths for the year.

The radon level has been confirmed to be on the high side is comparison to many cities in the world [4]. The average radon concentrations for offices, factories, schools, public places and hospitals were 77Bq/m^3, 76 Bq/m^3, 43Bq/m^3, 64Bq/m^3 and 55Bq/m^3, respectively [12]. The figures for recent surveys showed that only 5.1% of public-place premises exceeded 200Bq/m^3 ([4] to [6]). The recommended action level for indoor radon concentration in the United States is 150 Bq/m^3 [2].

1 TEORIJA

1 THEORY

Spremembo koncentracije radona s stopnjo izmenjavanja zraka lahko ponazorimo z naslednjo enačbo:

The variation of radon concentration with air-exchange rate can be illustrated by the following equation:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \lambda C + \frac{\sum E_j A_j}{V} + \frac{q(C_0 - C)}{V} \tag{1}$$

$$C = \left(C_i - \frac{\sum E_j A_j + qC_0}{V\left(\lambda + q/V\right)} \right) e^{-\left(\lambda + \left(q/V\right)\right)t} + \frac{\sum E_j A_j + qC_0}{V\left(\lambda + q/V\right)} \tag{2}$$

Ker je $\lambda << \frac{q}{V}$, je ustaljena rešitev naslednja:

Since $\lambda << \frac{q}{V}$, the steady-state solution becomes:

$$C_{(\infty)} = C_0 + \frac{\sum E_j A_j}{q} \tag{3}$$

Iz enačbe (3) vidimo, če ima stavba veliko število izmenjav zraka, potem je koncentracija radona zunaj in znotraj poslopja približno enaka. Izraz $\Sigma E_j A_j$ je v povezavi s kritično rastjo krivulje radona v prostorih, ko je C_i blizu C_0.

Diferencialna enačba (2) z upoštevanjem časa, ko gre ta proti nič, je naslednja:

From equation (3), if a building is under strong ventilation conditions, the indoor radon concentration is approximately the same as the outdoor radon concentration. The emission term $\Sigma E_j A_j$ is related to the critical radon growth curve at the premises if C_i is assumed to be close to C_0.

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

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

Potem je:

Then:

$$\Sigma E_i A_i = M_i V \quad (5).$$

Enačbo (5) vstavimo v enačbo (3):

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

$$C_{(\infty)} = C_0 + \frac{M_i}{q}$$

ali

or

$$\frac{C_{(\infty)}}{C_0} = 1 + \frac{M_i}{C_0(ACH)} \quad (6).$$

2 NDT SIMULIRANJE

Za proučevanje zračnih tokov in onesnaženega zraka v stavbah imamo na voljo dva postopka: eksperimentalno raziskavo in računalniško simuliranje. Najbolj stvarne informacije glede notranjih zračnih tokov in onesnaženega zraka dajo neposredna merjenja, to so: porazdelitev hitrosti zraka, temperatura, relativna vlažnost in stopnja onesnaženosti. Ker morajo biti ta merjenja opravljena na več krajih, so neposredna merjenja porazdelitve zelo draga in vzamejo veliko časa. Celotno merjenje lahko zahteva več mesecev dela. Za dosego končnih rezultatov morajo biti dovod zračnih tokov in temperatura iz hladilnih, prezračevalnih in klimatskih sistemov (HPK - HVAC) ter temperature prostorov stalne med celotnim merjenjem. To je še posebej težko doseči, saj se zunanji pogoji časovno spreminjajo in se glede na to spreminjajo tudi temperature prostorov, zračni tok in temperature iz sistemov HPK.

Zračni tok in onesnažen zrak lahko določimo z rešitvijo več enačb, ki upoštevajo tok, energijo in onesnaženje v sistemu. Zaradi omejitev pri eksperimentalnem postopku, zmogljivejših računalnikih numerična rešitev teh enačb omogoča preprosto izbiro za določanje zračnega toka in porazdelitve onesnaženosti v stavbah. Ta metoda se imenuje NDT (numerična dinamika tekočin).

Metoda NDT je zelo uporabna za analizo notranjega okolja, kakor so vzorec zračnega toka in porazdelitev hitrosti zraka, temperatura, intenzivnost turbulence in koncentracija onesnaženosti. Zaradi omejene moči in zmožnosti računalnika mora biti model turbulence uporabljen v tehniki NDT, da bi rešili problem gibanja toka. Uporaba modelov turbulence vodi k nezanesljivosti izračunanih rezultatov, ker modeli niso splošni. Zato je pomembno, da v ta program vnesemo eksperimentalne podatke [15].

Model NDT, ki temelji na modelu RNG *k*-e in funkciji zidu [11], je bil uporabljen pri zbiranju podatkov za značilno pisarno v Hong Kongu (sl. 1). Celoten prostor mora biti razvrščen v omejene prostornine po mrežnem sistemu. Spremenljivke toka, kakor so hitrost, temperatura in koncentracija,

2 CFD SIMULATIONS

Two main approaches are available for the study of airflow and pollutant transport in buildings: experimental investigation and computer simulation. In principle, direct measurements give the most realistic information concerning indoor airflow and pollutant transport, such as the distributions of air velocity, temperature, relative humidity, and contaminant concentrations. Because the measurements must be made at many locations, direct measurements of the distributions are very expensive and time consuming. A complete measurement may require many months of work. Moreover, to obtain conclusive results, the supply airflow and temperature from the Heating Ventilating and Air Conditioning (HVAC) systems and the temperatures of the building enclosure should be kept unchanged during the experiment. This is especially difficult to achieve because the outdoor conditions change with time and the temperatures of the building enclosure and the airflow and temperature from the HVAC systems will also change accordingly.

Alternatively, the airflow and pollutant transport can be determined computationally by solving a set of conservation equations describing the flow, energy, and contaminants in the system. Due to the limitations of the experimental approach and the increase in performance and affordability of high-speed computers, the numerical solution of these conservation equations provides a practical option for determining the airflow and pollutant distributions in buildings. The method is the Computational Fluid Dynamics (CFD) technique.

The CFD technique is a powerful tool to analyse indoor environment problems, such as airflow pattern and the distributions of air velocity, temperature, turbulent intensity, and contaminant concentrations. Due to limited computer power and capacity available at present, turbulence models have to be used in the CFD technique in order to solve flow motion. The use of turbulence models leads to uncertainties in the computed results because the models are not universal. Therefore, it is essential to validate a CFD program with experimental data [15].

A validated CFD model based on the RNG *k*-ε model and wall function [11] was used to generate data for a typical office in Hong Kong (Figure1). The whole computational domain, the space of the room, needs to be divided into a number of finite volumes using a grid system. The flow variables, such as velocity, temperaso računani na sredini omejene prostornine. Pri manjši omejeni prostornini so rezultati bolj natančni, kar pa pomeni več časa za izračun.

Prostornina, površina tal in površina sevanja radona v modelu pisarne so bili 48,93 m^3, 20,07 m^2 in 79,15 m^2. Predpostavljeno je bilo, da sta v pisarni dve osebi (oseba 1, oseba 2). Tam sta bili dve dovodni in ena odvodna rešetka, nameščene na stropu. Z uporabo ventilatorja je bil doveden 100% svež zrak, s prilagodljivo stopnjo prezračevanja v pisarno prek dovodnih rešetk. Predpostavljeno je bilo, da so vsa vrata in okna zaprta in se zrak odvaja prek odvodne rešetke. Radon je seval z betonske površine in notranja koncentracija radona se je postopno povečevala do določenega nivoja glede na različne stopnje izmenjav zraka. Imamo tri strategije za nadzor radona v notranjih prostorih: z večanjem stopnje izmenjavanja zraka, z zmanjševanjem dotoka radona in s povečanjem odstranitve notranjega radona. Za študijo je bila izbrana prva strategija.

Simuliranje je temeljilo na 0,5 izmenjav zraka na uro (IZU - ACH), 1,3 IZU in 4 IZU za določitev porazdelitve radona v prostoru. Koncentracija radona v prostoru je bila ocenjena pri 1,2 m od tal, kar naj bi pomenilo cono dihanja v sedeči legi.

Prejšnje raziskave so potrdile, da različni končni gradbeni materiali (npr. plastična tapeta) učinkovito zmanjšujejo koncentracijo radona v prostoru [7]. Da bi naredili analizo z največjimi koncentracijami radona, so v tej raziskavi na tleh, stenah in stropu opustili končne gradbene materiale. Izraz za notranjo koncentracijo radona (Bq/m^3) z določeno spremembo zraka na uro z dano stopnjo rasti radona M_i je definirana z enačbo 6.

V enačbi uporabimo ρ_{betona} = 2450 kgm^{-3}, x_j = 0,125 m, E_{betona} = 21x10^{-6} Bqkg^{-1}s^{-1} [3], C_0 = 15 Bq/m^3, $C_{(\infty)}$ = 200 Bq/m^3, A_j = 79,12 m^2, V = 48,93 m^3 in dobimo oceno za stopnjo rasti radona m_i približno 74,90 Bqm^{3}h^{-1}.

ture and concentration, are solved at the centre of each finite volume. The finer the grid is, the more accurate the results will be. However, fine grid will require more computing time and capacity.

The volume, floor area and radon-emitting surface area of the office model were 48.93m^3, 20.07m^2 and 79.15m^2 respectively. It was assumed that 2 occupants (named occupant 1 and occupant 2) were inside the office. There were two supply air grilles and one return air grille installed in the ceiling. With the use of a fan, 100% fresh air with an ajustable ventilation rate was supplied to the office via the supply air grilles. It was assumed that all the doors and windows were closed and that the air was discharged through the return air grille. The radon was emitted from the concrete surface and the indoor radon concentration was gradually accumulated up to a steady level under different air-exchange rates. There are 3 strategies for controlling indoor radon: by increasing the air replacement rate; by lowering the input rate of radon and increasing the indoor removal rate. The first of these will be selected for the study.

The simulation was based on 0.5 air changes per hour (ACH), 1.3 ACH and 4 ACH to determine the radon-gas distribution inside the room. The indoor radon concentration was evaluated at 1.2 m from the floor to simulate the breathing height of a person seated in the room.

Previous studies have confirmed that different finishing materials (e.g. plastic wallpaper) effectively reduce the indoor radon concentration [7]. For the purpose of carrying out the worst case analysis of the indoor radon concentration it was assumed in this study that no finishing materials were applied to the floor, wall or ceiling. The formula for the indoor radon concentration (Bq/m^3) for a definite air change per hour with a given radon growth rate (M_i) is defined by Equation 6.

Applying this equation with $\rho_{concrete}$ = 2450 kgm^{-3}, x_j = 0.125 m, $E_{concrete}$ = 21x10^{-6} Bqkg^{-1}s^{-1} [3], C_0 = 15 Bq/m^3 , $C_{(\infty)}$ = 200 Bq/m^3, A_j = 79.15 m^2, V = 48.93 m^3, gives an estimate for the radon growth rate (m_i) of approximately 74.90 Bqm^{3}h^{-1}.

$$\frac{C_{(\infty)}}{C_0} = 1 + \frac{m_i}{C_0(ACH)}$$

$$\frac{200}{15} = 1 + \frac{74{,}90}{15(ACH)}$$

$$ACH = 0{,}4 \text{ h}^{-1}$$

V tem primeru je najmanjše število izmenjav zraka na uro približno 0,4 za zagotovitev, da stanovalca nista izpostavljena notranji koncentraciji radona, ki znaša maksimalno 200 Bq/m^3.

3 REZULTATI IN RAZPRAVA

Notranja koncentracija radona za osebi 1 in 2 je prikazana glede na stopnjo prezračevanja na sliki 2. Sobna koncentracija radona z različnimi stopnjami izmenjav je prikazana na slikah 3 do 8.

Thus, the minimum number of air changes per hour to ensure that the occupants are not subject to a high level of indoor radon concentration (200 Bq/m^3) as approximately 0.4.

3 RESULTS AND DISCUSSION

The indoor radon concentration for occupants 1 and 2 are plotted against the ventilation rate and the result is presented in Figure 2. The room's radon concentration with different exchange rates is shown

Prereza *X-X′* in *Y-Y′* pisarne sta prikazana na sliki 1.

Masa plina v radonu glede na celotno količino zraka:

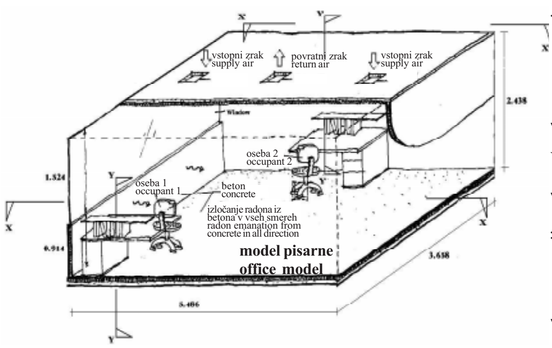
in Figure 3 to 8. The positions of Section *X-X'* and *Y-Y'* are shown in Figure 1.

The mass fraction of radon gas is the mass of radon divided be the total mass of the air mixture:

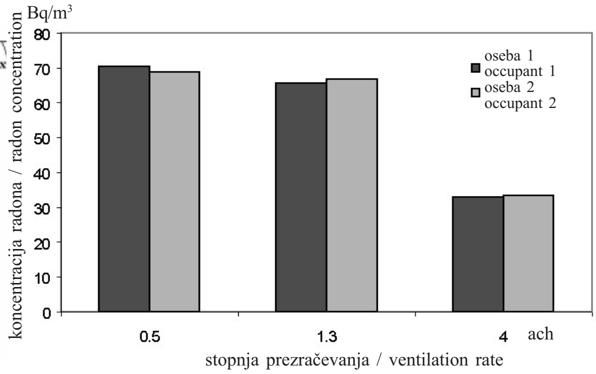
$$1\mathrm{Bq/m^3} = \frac{1\times 1{,}6\times 10^{-20}\times 9{,}96}{1\times 1{,}205} = 1{,}3225\times 10^{-19}\,\mathrm{kg/kg}$$

kjer je gostota plina radona in zraka 1,6 x 10^{-20} kg/m^3 in 1,205 kg/m^3 [4].

where the density of radon gas and air are 1.6 × 10^{-20} kg/m^3 and 1.205 kg/m^3, respectively [4].



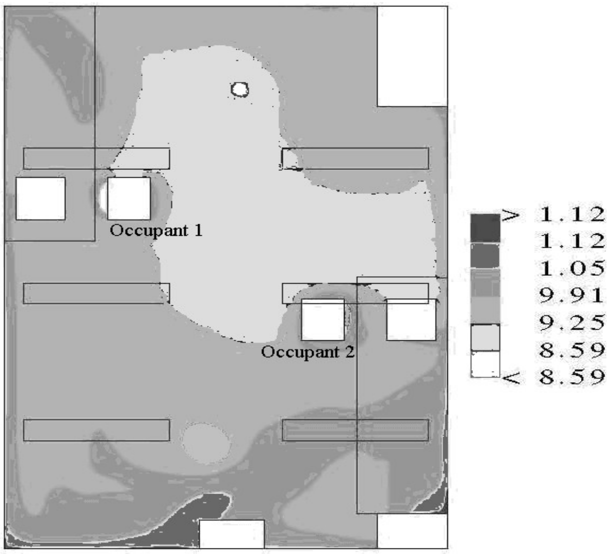
Sl. 1. *Izmere in razporeditev pisarne*
Fig. 1. *Model office dimensions and layout*



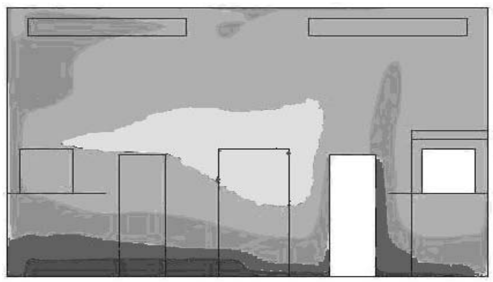
Sl. 2. *Sprememba notranje koncentracije radona kot IZU za osebo 1 in 2*
Fig. 2. *Variation of indoor radon concentration vs ACH for occupants 1 and 2*

Na sliki 2 je zelo jasno vidna usmeritev, da se stopnja radona zmanjšuje s stopnjo izmenjavanja zraka. S stopnjo izmenjavanja zraka 0,5 IZU je največja koncentracija radona enaka 70 Bq/m^3 in 68,5 Bq/m^3 za osebi 1 in 2, kar je veliko manj od 200 Bq/m^3 – priporočena stopnja. Poleg tega je koncentracija radona za osebi 1 in 2 več ali manj enaka, ko jo primerjamo z učinki prezračevanja.

In Figure 2, a very clear trend was observed, the radon level decreased with air-exchange rate. With an air-exchange rate of 0.5 ACH, the maximum radon concentration is found to be equal to 70 Bq/m^3 and 68.5 Bq/m^3 for occupants 1 and 2, respectively. These levels are much lower than the 200 Bq/m^3 recommended action level. Additionally, the radon concentration for occupants 1 and 2 is more-or-less the same when compared with the effect of ventilation.



Sl. 3. *Sobna koncentracija radona v Bq/m^3 pri 0,5 stopnji izmenjavanja zraka in višini 1,2 m (prerez X-X′)*
Fig. 3. *Room radon concentration in Bq/m^3 at 0.5 air-exchange rate and 1.2 m height (Section X-X')*



Sl. 4. *Sobna koncentracija radona v Bq/m^3 pri 0,5 stopnji izmenjavanja zraka (prerez Y-Y′)*
Fig. 4. *Room radon concentration in Bq/m^3 at 0.5 air-exchange rate (Section Y-Y')*

Na slikah 3 in 4 vidimo, da se sobni zrak redno toda počasi zamenjuje z zunanjim zrakom s procesom izmenjavanja zraka. Zaradi te skrajno nizke stopnje izmenjavanja zraka je kroženje zraka majhno in zato so se pojavile v kotih pisarne mrtve cone s sorazmerno visoko koncentracijo radona. V splošnem je srednja vrednost koncentracije radona približno 70 Bq/m^3, največja vrednost je le 90 Bq/m^3. Najvišja vrednost se je pojavila le v kotih pisarne, kjer pa se ljudje ne zadržujejo.

S povečanjem stopnje izmenjavanja zraka na 1,3 ACH (2,6 krat) se koncentracija radona zmanjša le za 8%. Količina radona v sobi je bila pod 70 Bq/m^3 pri 1,2 m nad tlemi, kakor je prikazano na sliki 5. Pri tej stopnji izmenjavanja zraka v določeni sobi je stopnja izmenjavanja svežega zraka 7,5 litrov/osebo/sekundo, kar je zahtevani minimum po standardu ASHRAE 62-1989R.

S primerjavo slik 3 do 6 opazimo razliko v zmanjšani koncentraciji radona in na slikah 7 in 8 je povprečna koncentracija radona 32 Bq/m^3. Ta izredno nizka stopnja koncentracije radona je posledica razmeroma visoke stopnje izmenjavanja zraka, ki tako ″izčrpava″ visoko stopnjo koncentracije iz prostora.

Lokacija in število teh dovodnih/odvodnih rešetk, lega pisarne itd. bodo vplivali samo na porazdelitev radona v pisarni in ne na koncentracijo radona v pisarni.

Ta model pa ima tudi omejitve. Kot prvo je bilo predpostavljeno, da je zunanja koncentracija radona nespremenljiva pri 15 Bq/m^3, vendar se le ta spreminja. Na zunanjo stopnjo

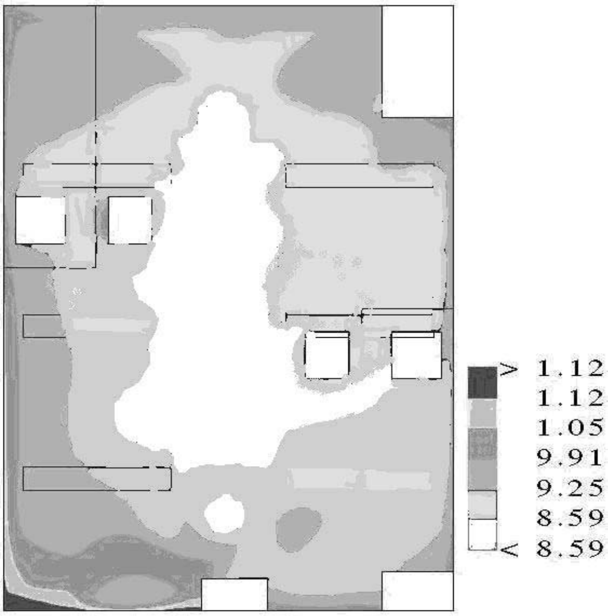
From Figure 3 and 4, we can see that the room air is constantly but slowly replaced by outdoor air via a forced-air-exchange process. With this extremely low air-exchange rate, the air circulation is low and some dead zones of relatively high radon concentration were found in the corners of the room. In general, the mean radon concentration is around 70 Bq/m^3 with the maximum value being only 90 Bq/m^3. The high values of radon concentration occurred at the corners of the room where the occupants are unlikely to be located for extended periods.

By increasing the air exchange rate to 1.3ACH (2.6 times), there is only a slight decrease of 8% in the radon concentration. However, a larger portion of the room's radon concentration was found to be below 70 Bq/m^3 at 1.2 m above the floor, as shown on Figure 5. Under this air-exchange rate and in this particular room, the fresh-air rate is about 7.5 litres/person/second, which is the minimum requirement as specified by the revised ASHRAE standard 62-1989R.

In compared with Figure 3 to 6, there is a marked decrease in the radon concentration in Figure 7 and 8 with an average radon concentration of around 32 Bq/m^3. This excessively low level of radon concentration was due to the relatively high air-exchange rate which brought in outdoor air of low radon concentration and exhausted the indoor air of relatively high radon concentration.

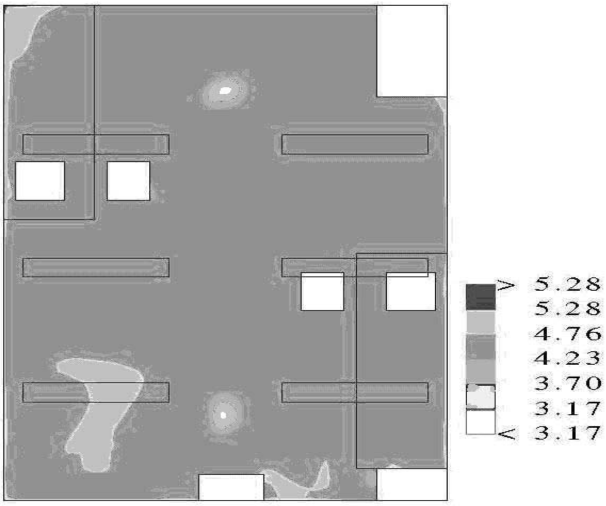
The location and number of the supply/return air grills, layout of the room, etc., will only affect the room's radon distribution, but not the overall radon concentration.

There are limitations in the model itself. First, it was assumed that the outdoor radon concentration is kept constant at 15Bq/m^3. However, it varies from place to place. The outdoor radon level is affected by meteo-

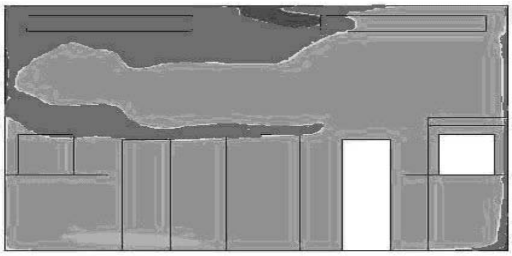


Sl. 5. *Sobna koncentracija radona v Bq/m^3 pri 1,3 stopnji izmenjavanja zraka in višini 1,2 m (prerez X-X′)*
Fig. 5. *Room radon concentration in Bq/m^3 at 1.3 air-exchange rate and 1.2 m height (Section X-X')*

Sl. 6. *Sobna koncentracija radona v Bq/m^3 pri 1,3 stopnji izmenjavanja zraka (prerez Y-Y′)*
Fig. 6. *Room radon concentration in Bq/m^3 at 1.3 air-exchange rate (Section Y-Y')*



Sl. 7. *Sobna koncentracija radona v Bq/m³ pri 4,0 stopnji izmenjavanja zraka in višini 1.2 m (prerez X-X')*
Fig. 7. *Room radon concentration in Bq/m³ at 4.0 air-exchange rate and 1.2 m height (Section X-X')*



Sl. 8. *Sobna koncentracija radona v Bq/m³ pri 4,0 stopnji izmenjavanja zraka (prerez Y-Y')*
Fig. 8. *Room radon concentration in Bq/m³ at 4.0 air-exchange rate (Section Y-Y')*

radona vplivajo meteorološke, topografske in geološke razmere [8]. Razlike so v zunanjem radonu, ki ga povzročajo dnevne spremembe. Najvišja koncentracija se pojavi ob zori, najnižja pa popoldne.

Model ne upošteva odvisnosti sevanja radona različnih gradbenih materialov. Različni gradbeni materiali povzročajo različne stopnje sevanja radona. Kakorkoli že so ti učinki zelo majhni v primerjavi s tistimi, ki jih povzročajo različni prezračevalni sistemi [14].

4 SKLEPI IN PRIPOROČILA

Ena od možnosti za zmanjšanje notranje stopnje radona je v dovajanju več svežega zraka v prostor, vendar s tem porabimo več energije.

Po pravilniku Hong Konga o stavbah iz leta 1984 je najmanjša stopnja svežega zraka za vsako nadstropje stavbe, ki je uporabljeno za pisarne oziroma stanovanja, dana s prezračevanjem, ki zagotavlja pet izmenjav na uro.

Ocenjena stopnja svežega zraka je bila daleč pod zahtevano količino. Tako lahko menimo, da radon v pisarnah v splošnem ni glavna skrb, čeprav je priporočljivo obdržati stopnjo radona na čim nižji ravni.

Kakorkoli že, zamisel je uporabna za inženirje, ki z izbiro prezračevanja, ki temelji na stopnji svežega zraka na osebo, učinkovito vplivajo na zmanjšanje deleža radona. Ustrezna stopnja prezračevnja pomeni pomemben dejavnik pri zmanjševanju notranje stopnje radona.

Glede na raziskavo 3 v letih 1995/96 ni nobena pisarna, ki je bila vključena v raziskavo presegla meje 200 Bq/m³, največja vrednost je bila

rological, topographical and geological conditions [8]. There will be a difference in the outdoor radon caused by the diurnal variation where the radon level peaks at dawn and reached its lowest value in the afternoon.

In addition, the model does not take into account the correlation between the radon emanation rate of different building materials. Different building materials will have different effects on the radon emanation rates which determine the indoor radon concentration. However, these effects have been found to be small when compared to those caused by different ventilation conditions [14].

4 CONCLUSIONS AND RECOMMENDATIONS

One of the ways to reduce the indoor radon level is to introduce more fresh air to the room. However, this will consume more energy.

According to the Hong Kong Building Regulations 1984, the minimum fresh-air rate for every storey of a building used as an office or habitation should be provided with ventilation enabling not less than 5 air changes per hour.

Since the estimated fresh-air rate is far below the amount required it can therefore be concluded that radon in the office is, in general, not a major concern, although it is always advisable to keep the radon level as low as practically possible.

The concept, however, seems to be useful as building-services engineers may develop a rule of thumb by picking up a certain ventilation limit based on fresh-air rate per person, so that radon mitigation can be carried out effectively. An adequate ventilation rate has been shown to be a powerful factor in reducing the indoor radon level.

According to the 1995/96 survey 3, is no surveyed office premises exceeded the 200 Bq/m³ limit, with the maximum value being 156 Bq/m³. The high

156 Bq/m^3. Visoka stopnja radona je nastala zaradi neustreznega prezračevanja in prekomerne gostote, kar je bilo ugotovljeno v tej študiji pa tudi v drugih raziskovalnih delih, npr. HKPED 1998. Srednja vrednost koncentracije radona v pisarnah je bila 77 Bq/m^3 in 80 Bq/m^3 v letih 1995/96 in 1992/93 [12]. Podobni rezultati so bili dobljeni tudi s simulacijo te raziskave.

level of radon was found to be caused by inadequate ventilation and excessive occupancy density, which was not only the finding of the present study, but also other research works, *e.g.* HKPED 1998. The mean radon concentration for the office was found to be 77 Bq/m^3 and 80 Bq/m^3 in 1995/96 and 1992/93 surveys, respectively [12]. The values found are similar to the simulation results of this study.

5 OZNAČBE
5 NOMENCLATURE

stopnja izmenjavanja zraka na uro	*IZU - ACH*	h^{-1}	air-exchange (ventilation) rate per hour
površina gradbenega materiala v prostoru	A_j	m^2	surface area of building material in the room
notranja koncentracija radona	C	Bq/m^3	indoor radon concentration
začetna notranja koncentracija radona	C_i	Bq/m^3	initial indoor radon concentration
izenačenje notranje koncentracije radona	$C_{(\infty)}$	Bq/m^3	equilibrium indoor radon concentration
zunanja koncentracija radona	C_0	Bq/m^3	outdoor radon concentration
stopnja sevanja radona gradbenega materiala j	E_j	Bqm^{-2}h^{-1}	radon emanation rate of building material j
stopnja rasti radona	M_i	Bqm^{-3}h^{-1}	radon growth rate
dotok svežega zraka	q	m^3/s	fresh air supply
dejanska prostornina pisarne	V	m^3	effective volume of the room, m^3
čas	t		time
debelina gradbenega materiala j	x_j	m	thickness of building material j
specifična teža gradbenega materiala j	ρ_j	kgm^{-3}	density of building material j
količina radona v volumnu	λ		volumetric radon generation

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6 REFERENCES

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