

Physical Factors Affecting the Interior Radon-Concentrations

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Received December 2, 2012; revised January 5, 2013; accepted January 18, 2013

ABSTRACT

Researchers have realized that radon-contaminated air inside buildings is a principal way of human exposure to certain healthy-risks. A model is developed to estimate radon concentrations which consider various parameters: in indoor air radon (radon-222) concentration, air permeability of ground, air pressure difference between outdoor and indoor at ground level, ventilation of building ground and number of air changes per hour due to ventilation. The radon-222 transport into building might dominated by diffusion, pressure driven flow or/and a mixture of both depending on the actual values of the various parameters. So, in several and regular periods of time: January, April, July and October, radon-222 concentrations have been measured in ten rooms of five elementary schools and in five rooms of one high school at Qena city (Upper Egypt). This has been carried out using alpha scintillation counters. We have noticed that in three rooms the value has exceeded $200 \text{ Bq}\cdot\text{m}^{-3}$ at the basement and only one room at the first floor, and all values have changed with respect to time and localization: They have decreased from July to January and from basement to first floor. For example, radon-222 concentrations obtained by exposing track detectors varied in the range from $20 \text{ Bq}\cdot\text{m}^{-3}$ up to $100 \text{ Bq}\cdot\text{m}^{-3}$. The experimental results of the present work have been well fitted with the presented model (calculations) which supports the validity of the presented model. So, to decrease the level of indoor air radon-222 concentrations and to reduce its harmful effects it is recommended to follow the suggestions in the present study and to limit as possible the use of ceramic in the building construction, increase the hours of ventilation and to restrict the use of underground floors in buildings, the underground Metro and garage parking should be carefully (and even mandatory) ventilated.

Keywords: Indoor Radon Concentrations; Theoretical Model; Environmental Parameters

1. Introduction

Radium (^{226}Ra) decays naturally to radon-gas radon-222. They both are member of uranium series (^{238}U). Radon-222 is noble gas which can be released to soil pores; migrate to the ground surface without any chemical reactions; then it can accumulate in buildings. Radon is poisonous gas in air that comes from natural sources such as ground and can harm the environment and the human health. Radon exists ubiquitously in air (all over the globe) and in particular in the indoor of buildings of all kinds. USA environmental protection agency (EPA) estimates that about 20,000 radon-related lung cancers occur per one year. All acts of radon-222-inhaling (and daughter-products) are a major source of natural radiation exposure which leads to lung cancer [1]. Any person, anywhere she/he lives, no matter he will expose to radon-222 in the air that she/he inhale. Moreover, because radon-222 attach to aerosol particles, it is considered as one of the principal causes to lung cancer. Bergman *et al.*

[2] have shown that moderate concentrations of radon increases significantly and even more than bouble in the presence of cigarette smoke (equal risk for passive and active smokers). Recent epidemiological studies (concerning the cause of epidemiologic of infectious diseases) due to radon-222 exposed-persons have demonstrated that even at the levels of radon-222 in homes, that there is a real probability of lung cancer [3]. In developed and rich countries, the problem of indoor radon-222 has received much inspection; and some developed countries have signed in with nation-wide radon-222 surveys [4]. On the other hand, very little attention has been devoted for non-developed countries, for example Egypt, to the problem of indoor radon-222. Moreover, radon-222 can easily be inhaled and then deposited in the lung (and respiratory tract in general) and thereby leads to high doses from alpha particle radiation ($4\text{He} + 2 \text{ cores}$) emitted by (radon-222), Polonium (^{218}Po) or/and Polonium (^{214}Po). The soil or the building-ground under the buildings are

the most important source of indoor radon-222 in Upper Egypt dwellings, while building material and household water from drilled wells are rarely the main cause of inside-radon-222 concentrations which are in the average level of $200 \text{ Bq}\cdot\text{m}^{-3}$. In another work, it has been shown that radon in water and fertilizers have important effects on the environment [5-7]. The concentration of radon-222 in water, building-ground or soil extends from less some thousands to more than some millions $\text{Bq}\cdot\text{m}^{-3}$ in soils abundantly rich in radium (radium-rich soils). Both ground and the air tightness of the foundation structure affect strongly the radon-222-concentration, for indoor radon-222 concentrations. Even invisible cracks in the foundation floor or very minute cracks in walls below the ground level may lead to important infiltration of radon-222 to the indoor air which affects drastically the safety parameters. Fleicher *et al.* [8] have demonstrated that homes, in northern New York State, that are more air tight have three times the radon-222 levels greater than those of normal homes.

International interest exists of reducing the inside-radon-222 concentrations to a level as minimum as possible. In different countries, Rahman and Tercy have reviewed the radon-222 control systems [9]. It should be noted that the "low-levels" of radon-222 in some days might not have the low values the day after. Different analysis to pre-estimate (and to model) the inside-radon-222 concentration is found in the scientific literature. For example, several authors have studied the different variations of radon-222 concentrations (seasonal variations) with prediction through model calculations [10-13]. Also, pre-estimation due to premier calculations, after these models, demonstrate that there is some contribution from the building materials. So, to give a satisfied estimation to the radon-222 concentration based on various factors and as a consequence, one will gain some information about which counter measures should be effectuated, will be an essential tool in this domain. However, these models have considered the inside-radon-222 concentrations either: By treating a part of some parameters or by prediction of some detailed and relatively complex equations covering only certain sides of the total indoor-radon-222 problem. Here, we will take, initially, into consideration some different climatic parameters then we will establish a comprehensive, simplified and ready-to-use model for estimating the radon-222 concentration in indoor air and we will consider several factors that can affect the radon-222 concentration in indoor air:

- 1) Radon-222 concentration in ground;
- 2) Radon-222 diffusion resistance of radon-222 barrier-resistance;
- 3) Air permeance of ground;
- 4) Air pressure difference between outdoor and indoor ground levels;

5) Ventilation of the building and number of air changes due to ventilation;

6) Radon-222 transport into buildings might be dominated by diffusion, pressure driven flow or a mixture of both depending on the actual values of the different factors;

7) Permeance of building materials which is a scale of ability of that material (or substance) to permit a continuous and steady flow of matter (or energy); it is expressed as the volume (number of liters) of gas diffused normally (at angle 90° with surface) in one hour through a square meter. Permeance is expressed in Liters/hour and denoted as $P = \mu\text{A/L}$ [14]. To minimize the radon-222 level concentration in indoor air, this model may be applied as a tool to select the effective and cheapest way to minimize the radon-222 level concentration in indoor air;

8) The data of the present contribution give evidence that the values of parameters (most of the transport of radon-222 from the building ground to the indoor air) are due to leakage driven by pressure differences through the construction.

2. Experimental Techniques

The inside-radon-222 concentration of radon-222 has been studied in five elementary schools (codes ES-1, 2, 3, 4 and 5) and one high school (code HS-1) in Qena (Upper Egypt) which have been carefully chosen so that the construction and operation do not vary significantly. For example, all the chosen dwellings are built from same materials: Iron structure, marble and concrete and cement, stones, sand and bricks. Most of these materials participate and contribute to indoor radon-222. These schools have been chosen to be representative of the region of Upper Egypt. Each building has ten rooms (with average size $3 \text{ m} \times 4 \text{ m} \times 3 \text{ m}$, m^3), with at least one window and a door which are poorly ventilated. Experimental method for radon-222 measurements are based on counting of α -particles due to the disintegration of radon-222 (and its daughters). Several devices are present in the literature, some are active and other ones are passive devices. We have utilized passive devices using the modified version of Marcov's method [15] which is sensitive to α -particles in the energy-spectrum of the radon-222. In addition, some undesired factors such as humidity, low temperature, moderate heating and light have minor effects on our method (solid state nuclear track detectors SSNTDs) [16,17]. We have used LR-115 Type 2 (Pelliculable) plastic track detectors (each with a size of about $1.5 \text{ cm} \times 2 \text{ cm}$). These track-detectors are fixed at the top inside a cylindrical cane where the effective (sensitive) lower surface of the detector is freely exposed to the emergent radon-222 in such way that it is capable of recording the alpha-particles resulting from the decay of radon-222 in

the cane [18]. The radon-222 detectors have been suspended at the center of the room-class. 8 detectors have been arranged in ordered-distribution all-over the classroom (at about 3 meters height). The exposure time, in all buildings, has been recorded from 15 June 2011 to 15 December 2011. Then, the detectors have been subjected to chemical processing in a 10 M analytical grade sodium hydroxide solution at $60^{\circ}\text{C} \pm 1^{\circ}\text{C}$, for 90 minutes, in a constant temperature water bath to enlarge the latent tracks produced by alpha particles from the decay of radon-222. Following the etching process, the detectors have been washed for half hour with tap water (running and cold). Then the detectors have been rewashed with distilled water and finally with a 50% water-alcohol solution. Some minutes drying in air, the detectors are now ready for tracking counting. An optical microscope (Zeiss at $400\times$ magnification) can then be used to count the etched tracks. Their concentration is estimated in track cm^{-2} . Moreover, the field of view (area) has been calculated using stage micrometer. Unexposed films (LR-115 type II detector) under identical etching conditions have been used to estimate the average background track concentration under standard and identical etching conditions. Then, the measured track concentrations have been corrected for background. The experimental tolerance (error $\pm 1\sigma$) in the track concentrations have been estimated by multiplying track concentration with the inverse of the square root of the total number of tracks (N) $- 1/2$, where N is the total number of tracks counted in each sample. To obtain good statistics of tracks, one should select about 70 - 130 fields of view in a random way on each of the detector surface. The track concentrations of the two detectors in each dosimeter, installed at a location, have been averaged. These track concentrations have been converted into radon-222 concentrations by applying the conversion factor for LR-115 type II detectors per Bq/m^3 . The calibration process for the dosimeters has been calibrated against a known activity of 226 Ra, $^{\circ}\text{C}$ (radon-222 source). The calibration coefficient for LR-115 nuclear track detectors obtained from the calibration experiment is 0.036 and 0.18 alpha-track $\text{cm}^{-2}\cdot\text{day}^{-1}$ per $\text{Bq}\cdot\text{m}^3$ of radon-222, respectively. These values are in good agreement with that reported by other investigators [16,19,20] activity concentration D_a has been calculated using $D_a = \rho i / (k \eta t_a)$: k is attenuation factor [21] from radon-222 transport through the polyethylene (PE) insulating foil [22], η is the calibration coefficient of the radon-222 measuring device in terms of alphatracks $\text{cm}^{-2}\cdot\text{day}^{-1}$ per $\text{Bq}\cdot\text{m}^3$ of radon-222 and t_a is the exposure time in hours. Most of buildings have no air-conditioning conditions and some rooms are ventilated by ventilators or simply by opening doors and windows. The measurements have been carried out in regular periods of time: January, April, July and October, to estimate the indoor air radon radon-222 concentrations. These periods have

been characterized by different climatic parameters, for example pressure and temperature and we have taken an average value for each period.

3. Model

3.1. Factors Affect Measurements against Radon

The estimation of indoor radon-222 concentrations for selected buildings is based on a combination of some (or all) of the following factors:

1) Sufficient high radon-222 diffusion resistance and air tightness under the ground floor of the building which are caused by sealing of surfaces (that separate the indoor occupied space from the soil or the application of radon-222 barrier-resistances or membranes).

2) Active (fan powered) or passive (no fan) soil depressurization which gives a combined effect of ventilation of the building ground and balancing the pressure difference between the indoor air and the surrounding soil.

3) Ventilation (balanced) of both occupied rooms (indoor air) and unoccupied spaces such as vent crawl spaces. In their experiment, Kokotti *et al.* [23] have shown that when tenants have increased the ventilation of their rooms, radon-222 level has significantly decreased. The most cost-effective solution for non-new buildings will usually be a combination of the previous three factors. The costs compared to the effectiveness are usually much lower for preventive measures in new constructions, than in existing buildings [3,4]. This work focuses on the air tightness of radon-222 barrier-resistance or so-called radon-222 membrane. An airtight construction is a premise for other preventive measures to function, e.g. sub-slab depressurization systems (SSDS). Analysis of different measures show that active SSDS usually are the most effective preventive measure as a stand-alone [24], assuming an air tight construction. A major problem for the policy-makers is to solve an important question: How to protect human health and safety from radon-hazards? Because ambient outdoor air is fairly considered good, but indoor air, on the other hand, could not be considered safe. Searching for indoor quality should face the fact that individuals are making their own air-quality [25].

3.2. Model to Estimate Indoor Radon Concentration

Simply, the indoor-radon-222 concentration (IRC) may be due to the influence of four parameters:

- 1) Ventilation and air leakage from indoor to outdoor (VAL);
- 2) Diffusion from outdoor (DOD);
- 3) Exhalation from building materials (EBM);
- 4) Diffusion from ground (DG).

So, can write that the total ICR = VAL + DOD + EBM + DG. The above mentioned parameters can estimate the IRC as shown in the following calculations. The ICR at steady-state may be expressed as:

$$D_a = D_a + P_w (D_e - D_a) \frac{A_w}{V} \left(\frac{1}{n} \right) + \nu (D_m - D_a) \frac{S}{V} \left(\frac{1}{n} \right) + P (D_g - D_a) \frac{A}{V} \left(\frac{1}{n} \right) \quad (1)$$

Also, ICR at steady state (Equation (1)) could be approximated as:

$$C_a \approx \frac{1}{1 + P_w \frac{A_w}{nV}} \left[(P + q\Delta p) \frac{A}{nV} \right] C_g \quad (2)$$

where D_a is the IRC indoor-radon-222 concentration in $\text{Bq}\cdot\text{m}^{-3}$, D_e is the outdoor-radon-222 concentration in $\text{Bq}\cdot\text{m}^{-3}$, D_m is the Building material-radon-222 concentration in $\text{Bq}\cdot\text{m}^{-3}$, D_g is the ground-radon-222 concentration in $\text{Bq}\cdot\text{m}^{-3}$, P_w is the radon-222 diffusion transmittance between indoor and outdoor air, *i.e.* through walls and roof in $\text{m}\cdot\text{s}^{-1}$ ($P_w = 1/R_w$), the radon-222 diffusion transmittance of radon-222 barrier-resistance or whole ground construction in $\text{m}\cdot\text{s}^{-1}$ ($P = 1/R$), R is the radon-222 diffusion resistance of radon-222 barrier-resistance or whole ground construction in $\text{m}\cdot\text{s}^{-1}$ ($P = 1/R$), R is radon-222 building material emission (exhalation) coefficient in $\text{m}\cdot\text{s}^{-1}$, S is the indoor surface area of radon-222 containing building material m^2 , A is the room (building) area towards ground in m^2 , V is the room (building) volume m^3 and n is number of air changes per hour due to ventilation, in-filtration and ex-filtration, through walls and roof as the floor is included in q (air change/hour), q is the air permeance of ground in $\text{m}^3/\text{m}^2\cdot\text{h}\cdot\text{Pa}$, Δp is the air pressure difference between outdoor ground and indoor air at ground level (Pa), A_w is the room (building) area towards outdoor air (m^2). Radon-222 resistance is defined as the capability of radon-222 to diffuse through the material, *i.e.* this means the answer of the simple question: How much a considered material does resist the flow of radon-222 through it? Also, one can note that P and R may include the total radon-222 diffusion transmittance and resistance, respectively. This means that the various building materials (for example concrete floor) in addition to the radon-222 resistance (or transmittance) of the radon-222 barrier-resistance is also included. The same analysis is valid for the permeance q ; as it may include the average air permeance of the building ground structure with all its perforations and air leakage in addition to the permeance of the various materials, *i.e.* not only of the radon-222 barrier-resistance. The term $(q\Delta pA)$ represents the air leakage ($\text{m}^3\cdot\text{h}^{-1}$). Ventilation of the building ground is not included in the model but might be seen in Equation (1) as a reduction of

an effective radon-222 concentration in ground, and thus be applied in the calculations. In addition, wind increases the air infiltration and ex-filtration and the total ventilation reduces the radon-222 concentration in indoor air and the product νD_m with unit ($\text{Bq}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) may be referred to as a radon-222 building surface material emission or “exhalation rate”. For economic reasons, authority’s trends accelerate towards the minimization of ventilation and infiltration rates in recent constructions which drastically increases the radon-222 level inside buildings. The majority of the “sick buildings” disorders are associated with poor indoor-air quality [26]. Also, the number of air changes per hour (n) includes air leakages between indoor and outdoor air through the walls and roofs. Equation (1) (the above mentioned model) gives the equilibrium of the steadystate situation where the decay of radon-222 is not included where radon-222 has a self-life of 3.8 days [3,4]. On the other hand, if one considers D_m constant, the presented model will give more correct data: D_m is constant means that an inexhaustible or continuously replenished radon-222 reservoir in ground is time-independent. However, in some of the more extreme cases where the radon-222 model will not give the correct data due to the decay of radon-222, we will be not considering the normal building anymore. Real buildings, above ground, are mostly neither airtight nor radon-222-tight because they have at least some ventilation (n is not zero) and windows and doors are partially or completely opened. For example, if we imagine the presence of an ideally-tight (ultra-tight) building where radon-222 diffusion is not permitted, the radon-222 disintegration and time-dependency will also affect ICR. In the present work, the outdoor-radon-222 concentration might be assumed to be null ($D_e \approx 0$). Similarly, if we consider that the radon-222 concentration in building materials ($D_m \approx 0$), the building materials will absorb radon-222 from the indoor air. Also, we may assume that the radon-222 concentration in the building ground is much higher than the radon-222 concentration in the indoor air ($D_m \gg D_a$). Similarly, if we consider that the radon-222 concentration in building materials ($D_m \approx 0$), the building materials will absorb radon-222 from the indoor air. Calculating and solving D_a from Equation (1) without the forgoing simplification yields the following expression for the radon-222 concentration in indoor air:

$$D_a \approx \frac{\left(1 + P_w \frac{A_w}{nV} \right) D_e + \nu \frac{S}{nV} D_m + (P + q\Delta p) \frac{A}{nV} D_g}{1 + P_w \frac{A_w}{nV} + \nu \frac{S}{nV} + (P + q\Delta p) \frac{A}{nV}} \quad (3)$$

where

$$P = 1/R \quad (4)$$

Also, one can write in a simple form:

$$\Delta p = \frac{M p_{1atm} g h}{R_{gas}} \left[\frac{1}{T_e} - \frac{1}{T_a} \right] \quad (5)$$

where h is the indoor-outdoor air pressure equilibrium height (meter), Δp is the air pressure difference between outdoor ground and indoor ground levels in Pascal P_a , R is radon-222 resistance of radon-222 barrier-resistance in s/m ($R = 1/P$), M is the air molar mass = 28.97 gram (mole)⁻¹, P_{1atm} is the air pressure at 1atm = 101325 Pa, g = gravitational acceleration on Earth $\approx 9.8 \text{ m}\cdot\text{s}^{-2}$, R_{gas} 8.31451 J(K·mol)⁻¹, T_a and T_e are the indoor and outdoor temperatures, respectively, in Kelvin.

The air leakage from the ground into the building is proportional to driving force due to the pressure difference Δp and Equation (5) can describe this driving force by the chimney/stack effect as:

$$\Delta p = (p_g - p_a) \approx p_e - p_a = p_0 - p_a = p_0 - (p_0 - \rho_e g h + \rho_a g h) = (\rho_e - \rho_a) g h \quad (6)$$

$$\rho_a = \frac{M p_a}{R_{gas} T_a} \text{ and } \rho_e = \frac{M p_e}{R_{gas} T_e} \quad (7)$$

where

$$P_a \approx P_e \approx P_{1atm} \quad (8)$$

Here the indoor (ρ_a) and outdoor (ρ_e) represent the air masses concentration, with P_a and P_e as indoor and outdoor air pressure and T_a and T_e as the indoor and outdoor temperature, respectively. If one denotes the air pressure at outdoor ground level p_0 and the air pressure in outdoor ground just beneath the radon-222 barrier-resistance is denoting p_g , the driving force for air leakages into the building from the underneath ground will be calculated after Equation (6). One can approximate the air pressure difference as: $\Delta p = P_g - P_a$, with $\Delta p = P_e - P_a = P_0 - P_a$, *i.e.* the air pressure difference between the outside air pressure at ground level P_a ($=P_0 \approx P_g$) and the indoor air pressure at ground level P_a . This means that the driving force or pressure difference Δp is approximately independent of the radon-222 barrier-resistance depth in ground hg , the ground air mass concentration ρ_g and temperature T_g , the latter temperature is varying according to location under the building. Thus, it is safe to approximate: Two remarks should be considered: 1) If the approximation in the last equation (Equation (8)) is not used, this will lead to nonstop values (an infinite series) for the pressure difference Δp . 2) this latter (Δp) is a positive value when $T_a > T_e$, *i.e.* when the indoor air temperature is higher than the outdoor air temperature. That is, the highest value of Δp occurs typically in winter time or in cold climates.

4. Results

Table 1 shows the experimental values of radon-222

concentration obtained in five elementary schools (codes ES-1, -2, -3, -4 and -5) and one high school (code HS-1) in Qena city.

In general, the indoor air radon-222-concentrations, D_a in all rooms is relatively low at all conditions; only it has reached little bit more than 200 Bq·m⁻³ in three classrooms. It is worth noting that in other localizations in Egypt (Alexandria city), these low concentrations have been also reported [1]. Even higher values (1000 Bq·m⁻³) have been recorded in east Europe [27]. Moreover, it is interesting to report that values greater than 12,100 ± 600 Bq·m⁻³ have been reported in King's valley at Luxor [28]. Perhaps these high values have been recorded at deep distances inside the ground where the probability of finding radium and its daughters (and consequently radon-222) increased. Because of different climates in the above mentioned locations, this comparison could not be true, and one can't simply ranks the radon-222 as high or low levels. Moreover, because of the interference of these factors on each other, the parameters affecting the inside-radon concentration (which are given in Equation (1)) are not really sufficient to represent the real situation; for example the geometrical aspects of any building affect the inside-radon concentration and more effective ventilation rate affects the pressure difference. The main task in these geometrics is to ensure a sufficient air-tightness of the radon barrier-resistance to minimize the indoor-radon concentration. For example, it is necessary to weld the various radon barrier-resistance joints to ensure this air-tightness.

5. Discussions

To fit the presented model to experimental values (**Table 1**), an appropriate value for the air permeance has been chosen $=q = 10^{-3} \text{ m}^3/(\text{m}^2\cdot\text{h}\cdot\text{Pa})$ and then we look for the most suitable values that fit the experimental data; then another value for q has been chosen and so on. After several iterative processes, one has found that the best fitting parameters that fit Equations (1) and (2) to the experimental data are as follows: $D_g = 5 \times 10^4 \text{ Bq}\cdot\text{m}^{-3}$, $R_w = 3 \times 10^7 \text{ s}\cdot\text{m}^{-1}$, $R = 2.6 \times 10^7 \text{ s}\cdot\text{m}^{-1}$, $v = 0 \text{ s}\cdot\text{m}^{-1}$, $q = 10^{-3} \text{ m}^3/(\text{m}^2\cdot\text{h}\cdot\text{Pa})$, $\Delta p = 1.7 \text{ Pa}$, $D_e = D_m = 0 \text{ Bq}\cdot\text{m}^{-3}$, $A_w = 196 \text{ m}^2$, $S = 296 \text{ m}^2$, $V/A = 2.4 \text{ m}$, $n = 0.25 \text{ h}^{-1}$, $h = 2.7 \text{ m}$, $T_a = 31^\circ\text{C}$, $T_e = 41^\circ\text{C}$. These parameters are evidently functioning of time throughout one year. We have kept some

Table 1. Radon density obtained in five elementary schools (codes ES-1, -2, -3, -4 and -5) and one high school (code HS-1) in Qena (Upper Egypt).

| Code School | ES-1 | ES-2 | ES-3 | ES-4 | ES-5 | HS-1 |
|--|------------|----------|----------|---------|----------|----------|
| D_a (Bq·m ⁻³) (Experimental) | 128.8 ± 30 | 132 ± 14 | 113 ± 21 | 77 ± 13 | 203 ± 54 | 122 ± 12 |
| D_a (Bq·m ⁻³) (Calculated) | 132 | 132.1 | 129.9 | 131.7 | 135.2 | 125.1 |

parameters constant and vary the inside-radon-222 concentration with different other parameters. **Figure 1** shows D_a as a function of radon-222 barrier-resistance, for different values of fitting parameters, e.g. D_g , n , q , Δp and R . As seen from **Figure 1**, D_a decreases, first sharply with radon-222 resistance, and then second, it tends to stabilize for higher radon-222-resistance values. For example, at some values of radon-222 resistance, D_a decreases with the permeance as shown in **Table 2**.

In **Figure 2**, we show the behavior of indoor-radon-222 concentration D_a as a function of ground-radon-222 concentration D_g on keeping all other factors constant, for example at certain values of radon-222 ground concentration, D_a increases with the ventilation rate as shown in **Table 3**. The inside-radon-222 concentration D_a is plotted against radon-222 resistance where the other fitting parameters are kept constant; for example: when the radon-222-ground concentration $D_g = 5 \times 10^4$ Bq·m⁻³. This is depicted in **Figure 1** where at low radon-222 concentrations D_a decreases rapidly where diffusion of radon-222 is dominant, while at higher resistance, radon-222 concentrations decreases in slower rate till approaching to a limit value given by the air-leakage. It is noticed that if the permeance q set to zero the inside-radon-222 concentration increases with low resistance concentrations. So, comparing the values in **Figure 1**,

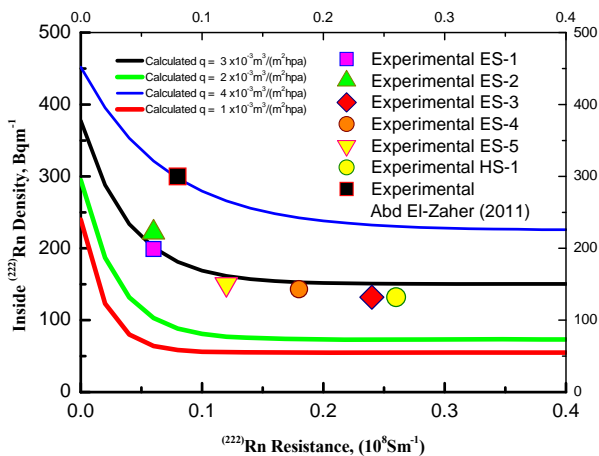


Figure 1. shows indoor radon density D_a as a function of radon-222 barrier-resistance, for different values of fitting parameters. Symbols show experimental results, and Black Square represents the data of Abd El-Zaher 2011 [1].

Table 2. Indoor radon density D_a as a function of ²²²Rn barrier-resistance, for different values of air permeance ²²²Rn-resistance ($s \cdot m^{-1}$).

| | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) |
|---|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1 | 80 | 74 | 73 | 73 |
| 2 | 168 | 154 | 150 | 150 |
| 3 | 279 | 248 | 225 | 225 |

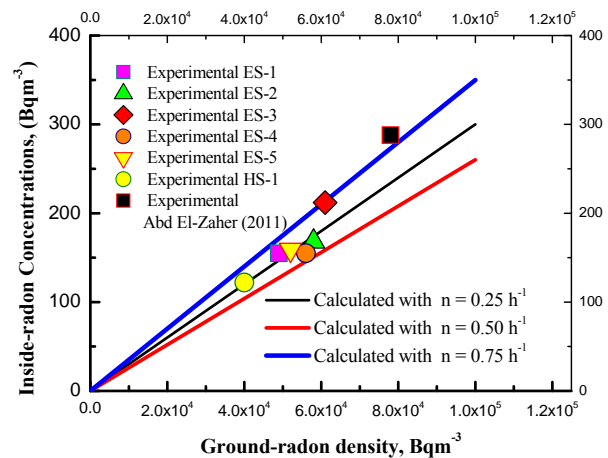


Figure 2. shows indoor radon density D_a as a function of radon-222 ground-density for different values of fitting parameters. Symbols show experimental results and black square represents the data of Abd El-Zaher 2011 [1].

Table 3. Indoor radon density D_a as a function of rate of air changes, for different values of ground-²²²Rn density D_g .

| D_a (Bq·m ⁻³) (Calculated) | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) | D_a (Bq·m ⁻³) |
|---|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| "n" (h ⁻¹) | 2×10^4 | 5×10^4 | 8×10^4 | 1×10^5 |
| 0.25 | 52 | 130 | 208 | 260 |
| 0.5 | 60 | 150 | 240 | 300 |
| 0.75 | 70 | 175 | 288 | 350 |

one can see that at higher radon-222 resistances (by diffusion) there is some contribution from the radon-222 diffusion to the inside-radon-222 concentration because most of radon-222 is carried out by simple air leakage. The behavior of indoor-radon-222 concentration D_a as a function of rate of air changes, n is depicted in **Figure 3** on keeping all parameters constant, for example at certain values of n , D_a increases with the pressure difference as shown in **Table 4**. This last behavior is important to keep considerable amounts of air changes per hour to maintain indoor-radon-222 concentration below some critical value. On the contrary, if we have low values of radon-222 resistance (low R) and high values of ground-radon-222 concentrations, then the indoor concentration of radon-222 will reach high values even with very effective (or even ultra-) air-tightness. This fact shows the importance to ensure high level of radon-222 resistance in the normal ground; for example by using ground-radon-222 barriers. Moreover, the indoor-radon-222 concentration D_a is depicted as a function of air permeance, for different values of radon resistances in **Figure 4**, for example at certain values of air permeance, D_a increases linearly with the radon resistances as shown in **Table 5**.

Another scenario that could help also: It is the ventilation of building ground might improve the situation be-

cause it decreases the radon-222 concentration in ground which, also, decreases the radon-222-resistance barriers.

The pressure difference, Δp is a linear function with D_a which is seen in **Figure 5**. This linear dependence of D_a with Δp is calculated after Equations (1)-(3). **Fi**

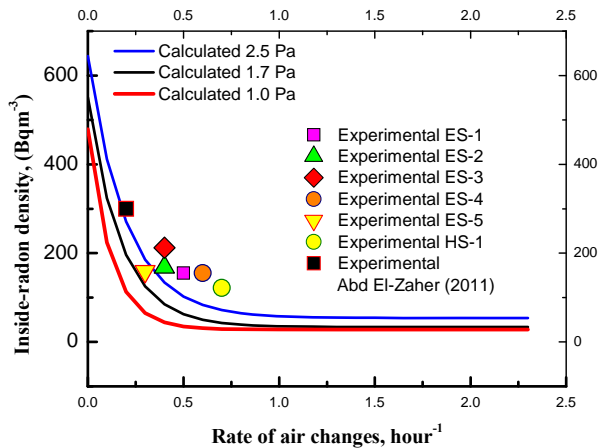


Figure 3. shows indoor radon density D_a as a function of rate of air changes, for different values of pressure difference between indoor and outdoor air. Symbols show experimental results and Black Square represents the data of Abd El-Zaher 2011 [1].

Table 4. Indoor radon density D_a as a function of rate of pressure difference (indoor/outdoor), for different values of rate of air changes.

| n (h^{-1}) | 0.1 | 0.25 | 0.5 | 0.75 | 1 |
|------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| p (Pa) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) |
| 0.25 | 225 | 95 | 49 | 37 | 38 |
| 0.5 | 340 | 155 | 57 | 48 | 49 |
| 0.75 | 410 | 233 | 105 | 68 | 70 |

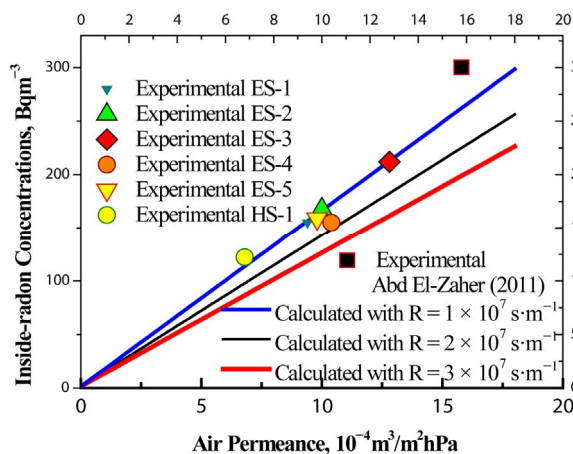


Figure 4. shows D_a as a function of air permeance, for different values of radon resistances. Symbols show experimental results and Black Square represents the data of Abd El-Zaher 2011 [1].

gure 4 shows the linear increasing of D_a as a function of the air-permeance: First, we have found that the suitable fitting parameters are as following: $D_e = 0$, $D_m = 0$, $D_g = 5 \times 10^4 Bq \cdot m^{-3}$, $R = 2.5 \times 10^8 s \cdot m^{-1}$, $n = 1/4 h^{-1}$ and $V/A = 2.3 m$. The radon-222-resistance could be considered as a typical value in vast range of building products: For example polyolefin products and bitumen. Then, second, if we consider that the suitable fitting parameters are: $D_e = 50 Bq \cdot m^{-3}$, $D_m = 0$, $D_g = 5 \times 10^4 Bq \cdot m^{-3}$, $R = 2.5 \times 10^8 sm^{-1}$, $n = 1/4 h^{-1}$ and $V/A = 2.3 m$, one will found the second linear behavior in **Figure 4**.

Similarly, if one considers that $D_e = 50 Bq \cdot m^{-3}$ and $D_m = 50 Bq \cdot m^{-3}$, we will find the third (higher) linear proportionality in **Figure 4**.

However, one should note that these barriers may prevent radon-222 from leaking through very minute (almost invisible) cracks in walls and floor-foundation [29, 30]. This picture shows clearly that a highly enough radon-222-resistance barrier (in the ground or the building structure facing the ground) makes air leakage occur through some uncertain (and/or accidental) “perforations”.

Moreover, **Figure 5** shows the indoor-radon-222 concentration D_a as a function of air pressure difference, for

Table 5. Indoor radon density D_a as a function of rate of pressure difference (indoor/outdoor), for different values of rate of air changes.

| Air permeance $m^2/(m^2 \cdot h \cdot Pa)$ | 5×10^{-4} | 10×10^{-4} | 15×10^{-4} | 18×10^{-4} |
|--|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| p (Pa) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) | D_a ($Bq \cdot m^{-3}$) |
| 1.0×10^7 | 66 | 128 | 188 | 227 |
| 2.0×10^7 | 72 | 140 | 217 | 256 |
| 3.0×10^7 | 80 | 171 | 246 | 298 |

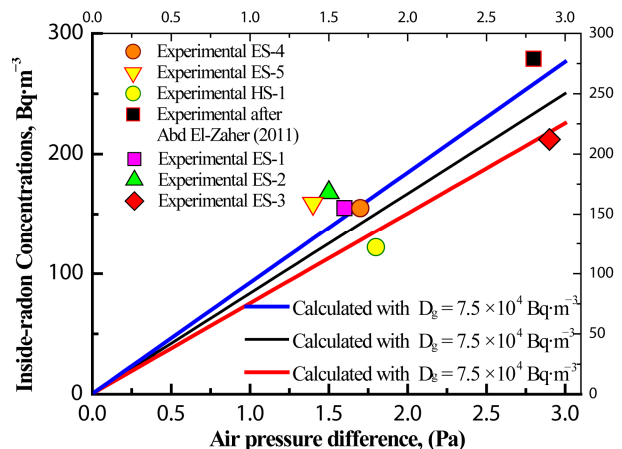


Figure 5. shows D_a as a function of air pressure difference, for different values of fitting parameters. Symbols show experimental results and Black Square represents the data of Abd El-Zaher 2011 [1].

different values of radon-222-ground concentrations, for example at certain values of air pressure, D_a increases linearly with the radon-222-ground concentrations as shown in **Table 6**.

As a general remark from these data, it is recommended that the minimum ventilation rate should be 0.5 air changes per hour. The mechanical movements of air particles, if they are ventilated, will ensure larger control of air exchange rate than the normal motion of wind. The indoor-radon-222 concentration is so sensitive to upon different sources of radon-222-leakage through the barriers. We summarize these different sources of radon-222-leakage by the term $q\Delta p$ which is somewhat crucial to ensure sufficient high air-tightness in the radon-222 barriers. The normal value of radon-222 concentration in ground D_g is $10^4 - 5 \times 10^4 \text{ Bq}\cdot\text{m}^{-3}$ and if D_g exceeds this range it will be considered as high radon-222 concentration.

We have calculated several cases with different fitting-parameters and we have arrived to the conclusion that it is mandatory to ensure very high air tightness. Even with a very high resistance radon-222-barrier, it may contain minute air leakages which indicate the importance of welding all joints and radon-222-barriers; in this regard aging factors of the building could be a principal cause to radon-leakage. We have taken the air-permeance value $q = 10^{-3} \text{ m}^3/(\text{m}^2\cdot\text{h}\cdot\text{Pa})$ which is an average air-permeance value for radon-222 for achieving the maximum security value; a standard value for q is $q = 5 \times 10^{-4} \text{ m}^3/(\text{m}^2\cdot\text{h}\cdot\text{Pa})$ which should not be taken into application because it does not include the radon-222-barrier connection (joint) towards the wall that enhances making large radon-222-leakage; thus higher value of air-permeance $q = 10^{-3} \text{ m}^3/(\text{m}^2\cdot\text{h}\cdot\text{Pa})$ is considered when fitting experimental values with model (**Figure 4**). Although the in-and-outdoor temperatures vary throughout the year, we have taken typical average values for this location, $30^\circ\text{C} \pm 1^\circ\text{C}$ and $40^\circ\text{C} \pm 1^\circ\text{C}$. Nevertheless, larger difference in temperatures stimulates a larger pressure difference between in- and out-door pressures, Δp , and consequently radon-222 concentration will increase. For normal buildings, the above ground radon-222 diffusion gradient could be neglected because the walls and roof have some radon-222-resistance, R . A typical value for radon-222-

resistance $R = 3 \times 10^7 \text{ s/m}$, which corresponds to transmittance value $P = 3.33 \times 10^{-8} \text{ m/s}$. If one starts by assuming large values of radon-222-resistance, R , this will give larger calculated values of indoor radon-222 concentration. Moreover, for normal n values ($0 < n < 1$), the D_e concentration is directly proportional to n for the equilibrium state conditions (steady state situation). This means that the values of “ n ” are replacing the inside-air to outside. In all figures, the experimental data are shown as symbols while the calculated values are illustrated as solid lines. The fit shows suitable and appropriate conditions between experimental and calculated values which supports the presented model.

6. Conclusion

The presented model has successfully been applied to fit experimental data which show the validity of this model. In order to maintain the indoor-radon-222 concentration as low as possible, the different calculations depict a nice picture giving rise to the importance of air-tightness of the radon-222-barrier, or generally rather the building structures, facing the building ground has to be ensured by securing sufficient air-tightness in joints and different feed-through and avoiding perforations. Also, continuous mechanical ventilation should maintain high rate of air exchange which will reduce also the pressure differences between indoor-air and outdoor-one. Moreover, the presented model gives realistic values and valuable information about the influence of different parameters on the indoor-radon-222 concentration which permits different choices to select a good and effective measure and low-cost to keep the radon-222 level as low as possible. After our model, the most effective source that affects the indoor-radon-222 concentration is the diffusion of ground-radon-222 to inside building through air leakages and cracks forced (driven) by pressure difference through the building-construction. It is really an urgent problem to protect public health from radon-hazards. Finally, one should provide his home with a smoke-free ambience.

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Table 6. Indoor radon density D_a as a function of $^{222}\text{R}_n$ barrier-resistance for different values of air pressure difference (indoor/outdoor).

| Air pressure Pa $R \text{ (s}\cdot\text{m}^{-1}\text{)}$ | $1.0D_a$ ($\text{Bq}\cdot\text{m}^{-3}$) | $1.5D_a$ ($\text{Bq}\cdot\text{m}^{-3}$) | $2.0D_a$ ($\text{Bq}\cdot\text{m}^{-3}$) | $2.5D_a$ ($\text{Bq}\cdot\text{m}^{-3}$) | $3.0D_a$ ($\text{Bq}\cdot\text{m}^{-3}$) |
|--|---|---|---|---|---|
| 2.5×10^4 | 75 | 113 | 149 | 182 | 225 |
| 5.0×10^4 | 80 | 125 | 162 | 208 | 251 |
| 7.5×10^4 | 84 | 172 | 180 | 228 | 273 |

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