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The Necessity of the Study of the Distribution of Radon Concentration in Residential Buildings

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ABSTRACT

Radon is the most harmful natural contaminant in the indoor atmosphere of the buildings. The noble gas, after cigarette smoke, is the biggest cause of lung cancer, and today the study of its diffusion, distribution, and concentration around the world has attracted many researchers in the field of radiation protection and environmental health. Typically, output data obtained from traditional methods of measuring radon concentration in indoor buildings is limited to information on the average radon concentration. Although these data are highly valuable in identifying buildings with a high risk of radon, it can be misleading to identify the real danger for residents of these buildings. In this research, by selecting a sample building and using numerical simulation based on the powerful method of computational fluid dynamics, the distribution of radon concentration in several important respiratory levels was investigated. The results indicate a non-uniform distribution of radon concentration in this building and they show that radon concentration in some of the major building sites can be up to 90% higher than the average radon concentration of the whole building. Therefore, in order to calculate the annual absorption dose in many buildings, it is necessary to study the distribution of radon.

Keywords: *Radon, Internal Contaminant, CFD, Concentration Distribution, Natural Ventilation.*

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1. INTRODUCTION

Radon (^{222}Rn) and its nuclear daughters decay indoors and endanger the human health. The origin of their presence in buildings is mostly due to the existence of their ancestors, namely, radium and thorium in soil and building materials. Today we know well that radon and her nuclear daughters are the agents of getting a major part (more than 50%) of the effective annual absorption dose by humans from the natural radiation and so checking and studying their behavior is very important (UNSCEAR Report, 1888). Previous studies have shown that the physical and environmental conditions such as rate and difference of temperature and humidity indoor and outdoor, the amount and type of indoor air ventilation as well as meteorological factors like wind, storm or rain can affect the indoor radon concentration (Singh et al., 2008).

The existence of these numerous factors effective on radon concentration makes estimation and calculation of its quantity in different points inside the building very difficult and so the results of most studies in this field such as Singh, K et al. in 2005, Murty, V.R.K and colleagues in 2010 and Dong, X and colleagues in 2016 are limited to present the average radon concentration inside the buildings (Singh et al., 2005; Murty et al., 2010; Dong et al., 2016).

Although this data, if it is the result of a long-term measure, is very valuable in identifying the buildings with high risk of radon but can be misleading in real danger identification for residents of these buildings; Because the data of average Radon concentration measured in a building may be less than the threshold concentration introduced by the international committee of protection against rays (100 Bq/m^3), but the typical location and respiration of residents in that building, has much more radon concentration than this limit. This lack of information is not so much acceptable in respect of safety protection principles of the quality of indoor air. Also, the world health organization emphasizes having the necessary information on levels of radioactive elements such as radon that may be carcinogenic (UNSCEAR, 2000). Thus in recent years, it has been tried to investigate the distribution of radon concentration in the buildings using powerful numerical methods like computational fluids dynamics (CFD). For example, using numerical simulation based on CFD method, Chuan and colleagues in 2014, Lee and colleagues in 2016 and Robbie and Ophi in 2017 modeled the distribution of radon concentration in the sample buildings (Chauhan et al., 2014; Lee et al., 2016; Rabi and Oufni, 2017).

Also in this research, by choosing one sample building and numerical simulation aided by computational fluids dynamics method, the distribution of radon concentration several important respiratory levels indoor was investigated. Also using a continuous precise measurement device, radon concentration was measured at the intended points and compared with the data obtained from the numerical solution. To validate the simulation results of Radon concentration distribution, the known relationships resulted from the analytical solution are also used.

2. MATERIALS AND METHODS

2.1. The sample building

In this study, in order to investigate the effect of various physical factors on the indoor distribution of radon concentration, a single sample building located in Shandiz area of Iran was used. This building (suite) has been built on a floor almost as even as the ground and formed of three connected areas i.e. hall, kitchen and dining room and the toilet and bath are outside the main building. The total area of this building is about 48 square meters and the height of the ceiling across it is about 3 meters (Fig. 1).

Approximate area of the hall is 24 square meters and the entrance door of the building with a width of 120 and height of 190cm is located at the eastern corner of its southern wall and below it, there is a gap of approximate height of 4 cm and as wide as the door that can be used as an entrance for fresh air to enter the building from outside and make a natural ventilation.

Bedroom and kitchen have the same dimensions and have been located in the north of the building as a rectangle cube with a length of 4 m and width of 3 m in parallel. Also, according to figure (1), there are two similar windows with dimensions of 100 by 50 centimeters and at a height of 2 meters from the ground in the middle of the northern walls of the bedroom and the kitchens. Although all walls, ceiling, and floor of the building have been covered with tiles and ceramics with a low diffusion rate of Radon, but due to a trivial leakage of the building in four areas below walls, relatively small but deep gaps have been created and are considered as the main source of Radon entering from the building bed into it. In Figure 1, they have been shown by names of Gap1 to Gap4.

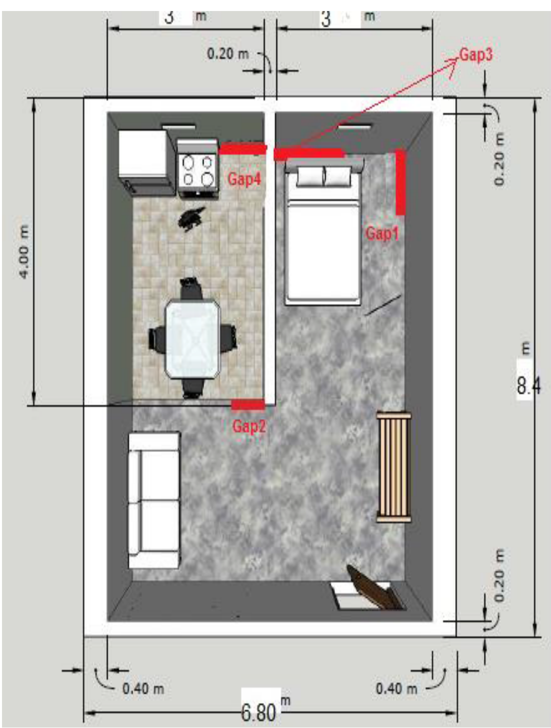

Figure 1: the three-dimensional model of the building in which entrance gaps for Radon and common locations of sleeping, sitting and standing of residents have also been specified.

2.2. Measurement chamber

To determine the diffusion rate of radon from the given surfaces and gaps, a cubic measurement chamber with a dimension of 40cm × 40 cm × 25cm was used of which all the surfaces have an impermeable plastic cover except one. When measuring Radon flaw going out the given surfaces, the radon measurement device is placed inside this chamber and its empty space volume at the presence of the device is almost about 0/032 m^3. Also the area of its open surface is 0/16 m^2.

2.3. Measuring device

In this research, for measuring the concentration of radon in different areas of the sample residential building, a portable radon measurement device of the RTM-1688 model made by Sarad Company in Germany was used. The sensitivity of this device during 300 minutes of continuous measuring is 13cts / (min × KBq / m 13). Simultaneous with measuring the concentration of Radon and Toron, this device can also measure temperature, pressure and relative humidity of the air and also, along with registering all this information, present analysis charts of Alpha spectrometer. In addition to the high accuracy of output data, the most important identifiers of this device are the high speed of responding in the fast mode and the low threshold of its sensitivity.

2.4. Computational Fluid Dynamics Method (CFD)

Using the numerical solution of the survival rules in the finite volume method and exploiting powerful software such as Fluent, we can solve the related equations set and simulate the fluid behavior. The general form of the survival rules for a fluid flux in a controlled small volume of C dependent variables is written as follows:

$$\partial(\rho c)/\partial t + \nabla.(\rho CV) = \nabla.(\rho D \nabla C) + S_c \qquad (1)$$

Where V is velocity, ρ is density, D is the diffusion coefficient of radon, and S_c stands for radon diffusion from the source.

The first sentence of this equation is called the changes time rate of the fluid element of variable C (unbalanced effect). The second sentence is the pure flux of variable C outside the fluid element (move effect), and the third sentence shows changes of change rate of C as a result of diffusion and finally the last sentence is the source of C production that actually specifies the change rate of fluid flux because of producing. It should also be considered that several limitations have been applied to

simplify in the numerical modeling in this research:

1. The effect of residents and furniture in the building is disregarded.
2. All gases in the building are assumed ideal.
3. Due to lack of accessing to real changes of the temperature of the walls and floor and ceiling during the simulation, their average temperatures are used constantly.

2.5. Analytical solution method

To estimate the concentration of radon in the sample building, a well-known analysis model was used. In this model, radon density is increased through the diffusion of radon from building surfaces and gaps and the process of radioactive Radon decay and air ventilation of the building are decreased.

Accordingly, Clavensjo and Akerblom in 1994 and Petropoulos and simopoulos in 2001 presented the final equation to determine indoor radon density in a closed room with a volume V as follows (Clavensjö and Åkerblom, 1994; Petropoulos and Simopoulos, 2001):

$$C_i(t) = C_0 e^{-\lambda t} + EA/V\lambda(1 - e^{-\lambda t}) \qquad (2)$$

where C_i is the indoor Radon density in the time t (s) and C_0 is the primary Radon density in t = 0 by Bqm^{3-}, E ($Bqm^{2-} h^{1-}$) is Radon inflow or Radon diffusion rate from soil and building materials, A (m^2) is the area of the surface from which radon diffuses, V (m^3) is the volume of the closed room and or the tested chamber, and λ (h^{1-}) is total rate of radon decay given by the following equation:

$$\lambda = \lambda Rn + \lambda V$$

Where λRn is the natural decay coefficient of radioactive radon and λV is the ventilation rate of the air inside the room or chamber. So the most important variable quantities in determining the indoor Radon density is Radon inflow into the room and air ventilation coefficient of the room. So if all the ways of air ventilation are closed (λV=0), the relationship 2 can be rewritten in the stable balance conditions as follows:

$$CMax = EA/V\lambda Rn$$

And by substituting the data related to radon diffusion rate from different gaps and building volume, the average amount of radon in the building can be obtained (Gupta et al., 2010).

2.6. Active measurement method

In order to focus the research on the critical points affecting human health, four levels at important heights from the floor were selected at which a mature man with a medium height often breathe the radon mixed in the air (Figure 2). Accordingly, Radon concentrations in each period for 6 important points of the sample to deploy the residents of this building has been described according to Fig. 1, along with the approximate time weight of everyday occupying these points by them in the table (1).

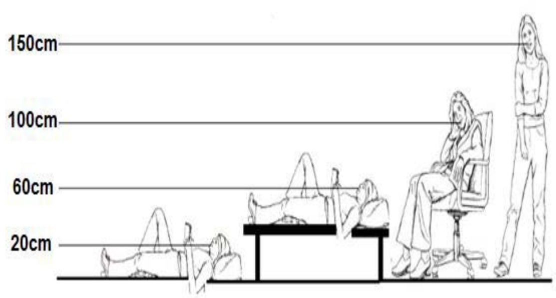

Figure 2: important breath heights for a mature man with a medium height in an everyday life have been specified in four levels.

Table 1: states, places, and approximate weight of everyday occupying by residents

Sample points	State – place	everyday occupying weight
1	Sleeping- bed- bedroom	0/45
2	Sitting – bed - bedroom	0/02
3	Sitting- chair - kitchen	0/10
4	Standing- in front of a stove- kitchen	0/05
5	Sitting – sofa- hall	0/20
6	Sleeping - in front of sofa - hall	0/10
7	Other places	0/08

It should be noted that the registered place in the explanations of this table is related to the approximate location of the residents' respirations in the described conditions. Complete coordinates of these points are also recorded in Table 3. By definition, everyday occupying weight for every location is a percent of the time duration of a day and night that the residents are present in that area.

As the data of this table show, more than 90% of the presence time of the residents of this building is spent at the 6 selected points and estimating radon concentration at them has a value weight much more than other points and thus in this research, empirical, numerical and analytical studies were focused on these points more.

Also, in order to calculate the average concentration of radon in this building, several separate measurements were performed at the altitude of 1/5 meters at the middle of the bedroom, kitchen, and hall. The average of these data is also listed in table (4).

3. RESULTS

3.1. Physical conditions

During the time span of January and February in 2017, radon concentration at the sample points inside the building was measured and according to its conditions, a numerical solution with Fluent software as well as an analytical solution was performed. All air ventilation ways of the building except the gap below the main door and window seams were completely blocked for a time of 10 days (860000s). Average input air temperature during this time was 16° C and the radon concentration inside it could be ignored. During this period, meteorology data shows that in most time, the moving direction of air outside the building was south-north, so during the ventilation, it is assumed that the fresh air has entered the building through the gap below the main door and gone out through the seams around the windows of its north side. By substituting and matching the measured data of temperature changes in the relations and the related thermodynamic patterns in these cases, the velocity of air entering and its corresponding ventilation coefficient were calculated. These patterns show the average velocity of air entering through the below part of the main door for a sample period, about 1mm per second. Also, according to the entering level of air and building volume, the air ventilation rate equivalent to this velocity was $\lambda v = 1/3 \times 10^{6-}$(1/s). Also it was tried to avoid the air disturbances by some arrangements when entering the building in order to record the results.

3.2. Radon entering rate

Floor and walls in the sample building in this study have been insulated by carpets and thick wallpapers and except for the four gaps in the floor specified in figure 1 by names of Gap1 to Gap 4, Radon rate diffused from other levels can be ignored. Radon diffusion rate from these gaps was measured using measurement chamber and the continuous measurement device described before and by substituting the required data in equation 2. The average of the obtained data has been shown in table 2.

Table 2: coefficients of Radon diffusion rate from the gaps.

Gap / Parameter	Gap1	Gap2	Gap3	Gap4
Location	Bedroom	Hall	Bedroom	Kitchen
Area (m^2)	$-4.9\times10^{2-}$	$3/1\times10^{2-}$	$9/2\times10^{2-}$	$2/8\times10^{2-}$
E (Bq/ m^2s)	0/19	0/16	0/13	0/12

3.3. simulation CFD

After creating and meshing the geometry corresponding to the described sample building by Gambit software, numerical solution, and simulation of the distribution of radon concentration was conducted by Fluent software and contours of Radon concentration were modeled based on the physical conditions of sample building and for the desired time. Figures 3 to 5 show contours of radon concentration for plates of Z = 4/5 m, Y = 0/6 m, Y = 1/0 m and Y = 1/5 m, respectively. These contours predict radon concentration changes in different places and heights of the sample building. Results of this simulation show that as it is expected, radon concentration in front of the entrance door of the building is very trivial due to the fresh air entering from the gap below it and increases around the entrance sources of radon.

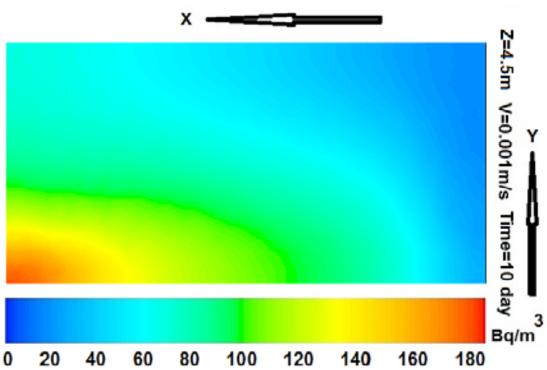

Figure 3: Radon concentration contour in the vertical plate z =4/5 m

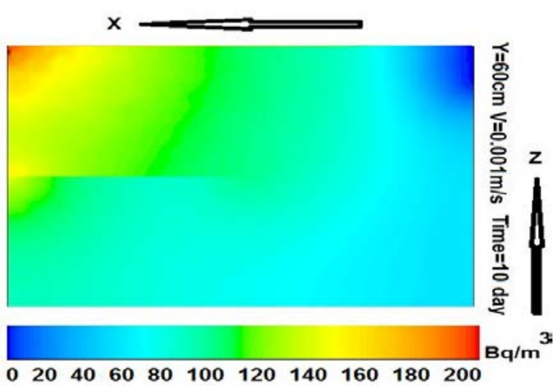

Figure 4: Radon concentration contour in the horizontal plate Y=0/6 m.

As an example and consistent to the contour of figure (4), all points located at the height of 60 centimeters from the bedroom floor have a Radon Concentration more than the permitted value (100Bq / m^3); while the upper contour of figure 5 shows that at the height of 1/5 meters from the ground, radon concentration in all building points is within the permitted range.

The results of this simulation for the 6 important respiratory points for the residents of the building (table 1) were compared with the experimental data resulted from measurements for the same points in Table (3). As seen, the maximum difference of the data at the corresponding places is about 15% indicating the relative conformity of the model resulted from CDF with the experimental results.

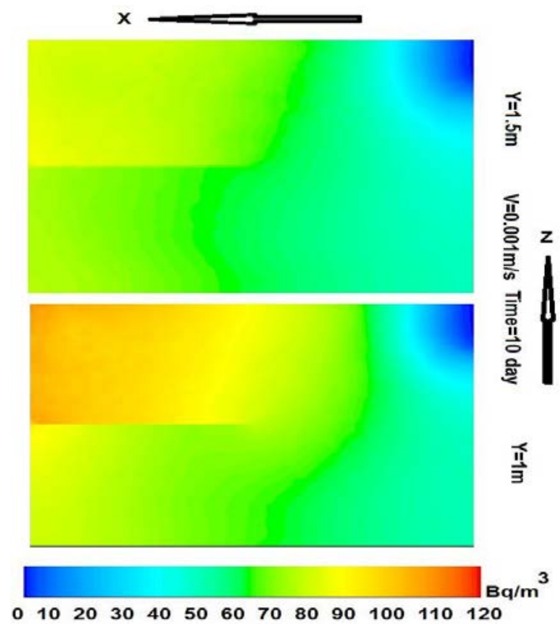

Figure 5: Radon concentration contours in the two plates of Y=1/0 m and Y=1/0.

A proper reference for validating the experimental and numerical data obtained for different points of the building is comparing their averages with the result of the analytical solution method. So for being sure about the correctness of the modeling performed by numerical solution, the average radon concentration that Fluent presents from integrating all the data in the total volume of the building, along with the average data resulted from measuring the concentration of radon at the middle points of the bedroom, kitchen and hall were compared with the result of the analytical solution in Table 4. As the acceptable match of the data shows, the correctness of the performed modeling can be approved.

Table 3: Radon concentration at 6 sample points of the building in terms of numerical and experimental data

	Coordinate(cm)			*C(Bq/m³)*	
	X	Y	Z	Numerical	Measurement
1	720	60	400	119.79	104±13
2	700	100	450	85.17	87±9
3	550	100	150	66.95	68±8
4	700	150	200	65.53	71±7
5	200	100	100	53.15	57±7
6	200	20	120	52.95	58±5

Table 4: The average data obtained from the methods of measurement, analytical solution and numerical solution for radon concentration in the sample building

Calculation Method	Analytical Solution	Numerical Solution	Measurement
$C(Bq/m^3)$	58±8	62.37	69±9

4. CONCLUSION AND DISCUSSION

In this research, a CFD 3D model has been used for research and development on distribution of Radon concentration in a sample building; in this state that for about 10 days, the poor natural ventilation has influenced the fluid flow in the sample building; Contours of Figures 3 to 5 have shown the distribution of radon concentration as uneven**.** These concentration changes are also observed in the results of most similar studies. As an example, as shown in the contour of Figure (6), Chuan and colleagues indicated that even in a room without ventilation, Radon concentration distribution can be variable (Chauhan et al., 2014).

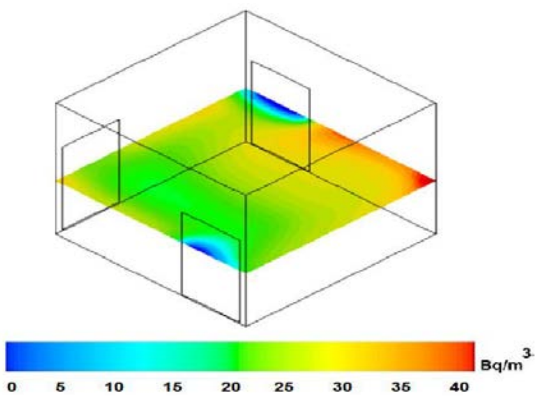

Figure 5: Contour of radon concentration in a sample room without ventilation in t = 97200s, Chuan and colleagues (2014).

Attending to the data of Tables 1, 3 and 4, it is specified that although the average of Radon concentration in this building has an average value about 60Bq / m^3, but the amount of this quantity at a point of the building with the highest coefficient of time occupancy weight (the residents' places of breathing when sleeping on the bed in the bedroom) is shown above 90 percent more than this average value. Also, these contours and data estimate that sitting and sleeping in the hall of this building are of low risk. Validating the experimental and numerical data by the numerical solution results, as shown in Table4, confirm the correctness of the performed simulation in this research too. Of course, more attending to the data of tables 3 and 4 shows that the results of the measurement are always a little more than the data resulted from the numerical solution for the corresponding points and quantities; Most likely its reason may be ignoring the radon diffusion values from other surfaces. Because as stated, though the diffusion coefficients from other surfaces are negligible, the sum of these small amounts of radon diffused over a long time can influence more on the results of the experimental measurements.

Finally, it must be admitted that although in the geometric simulation of the building and numerical modeling of Radon concentration distribution, accessing at the required information and equipment is so difficult in many cases, but the results of this research, as similar researches, emphasize the importance of examining the distribution of radon concentration, especially in the buildings with insufficient ventilation; so, according to the importance of the indoor radon threat to human health, it is necessary to research on this field extensively using powerful equipment and software and considering the impact of the ventilation devices, furniture and residents in the buildings is required.

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