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Investigating the Distribution of Indoor Radon Concentration in a Typical Residential Building

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A B S T R A C T

Radon is a radioactive gas that is now considered one of the most harmful natural factors in residential areas worldwide. After cigarettes, radon gas is considered the leading cause of lung cancer. Therefore, it is essential to study the measurement of radon concentration in different parts of the building. In this research, by choosing a sample building, the distribution of radon concentration in various regions using Computational Fluid Dynamics (CFD) in two conditions, non-ventilation and natural ventilation. The results were then compared with measurements from a continuous work radon detector under similar condition. Additionally, the average radon concentration in the building and different conditions was compared with data obtained from the analytical method. The results show that the modeling performed in a non-ventilation method with an error of less than 16% is consistent with the experimental data. Also in natural ventilation conditions, the experimental results confirm the numerical modeling results. On the other hand, the results derived from the analytical solution in both non-ventilation and natural ventilation conditions confirm distribution of radon concentration as simulataed. This study emphazizes the importance of identifying suitable locations for sleeping, sitting, and standing in a building, to minimize exposure to radon gas.

Keywords: Radon; Natural ventilation; Computational fluid dynamics (CFD); Analytical method.

1. Introductions

In developed countries, people spend an average of more than 85% of their time indoors, weather in houses, offices, schools, and so on. While buildings are meant to provide shelter for elements like heat, cold, sunshine, noise, they may not be as safe as perceived due to potential indoor pollutants. These pollutants can negatively impact the quality of the indoor air,

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ultimately posing risks to human health. Unfortunately, there is a constant rise in the variety of pollutants present [1].

Studies have shown that, following cigarettes, radon (222Rn) is the leading cause of lung cancer (UNSCEAR, 2000) and is among the most harmful pollutants found in homes in various countries, including Scandinavia, the United Kingdom, and the United States. It is believed approximately half of the public's exposure comes from radon and its byproducts. Radon is responsible for over 3,000 and 21,000 annual lung cancer deaths in the UK and the United States, respectively [2-3].

In recent years, with a better understanding of the internal damage caused by radon to human health, more precise research is needed. This is especially important due to the increasing use of closedventilation systems like fan coils, chillers, radiators, floor heating, and air conditioners in residential, offices, and educational settings. Research shows that the average radon content in residential houses is about 48 Bq/m^3, while in open environments it is about 15 Bq/m^3. However, it is crucial to note that these levels can vary significantly in different locations [4].

Traditional methods of measuring indoor radon only provide an average reading for an entire building or one room over a year. The lack of information in such methods is not acceptable in terms of the safety principles of indoor air quality.

The World Health Organization emphasizes the importance of on having data on radioactive elements like radon, which can be carcinogenic [5].

Most of the research conducted on indoor radon up to the present has focused on measuring average air concentrations in a few buildings. While this information is helpful for identifying areas and buildings at potential risk for radon exposure, it is not sufficient for accurately predicting the risk to residents. For instance, the specific locations where people breathe while sleeping, sitting, and engaging in daily activities are crucial factors that must be considered more effectively than areas that are less frequently used.

Most of the research conducted on indoor radon up to the present has focused on measuring average air concentrations in a few buildings. While this information helps identify areas and buildings at potential risk for radon exposure, it is not sufficient for accurately predicting the risk to residents. For instance, the specific locations where people breathe while sleeping, sitting, and engaging in daily activities are crucial factors that must be considered more effectively than areas that are less frequently used.Many scientists investigated the effect of physical factors such as temperature variations, humidity, geological characteristics, and rainfall on the average indoor radon concentration [7-9].

By using Computational Fluid Dynamics (CFD), researchers have analyzed and reported the distribution of radon concentration based on the physical characteristics of the room, as well as the effect of proper ventilation on reducing indoor radon levels [10-13].

In this study, the distribution of radon concentration across variouslocations and also under different physical conditions was examined using a selected sample building from

March 2017 to January 2018. Given the dynamical complexity of radon distribution within building interiors, in addition to the usual measurements, Computational Fluid Dynamics (CFD) method employed alongside standard measurements. Using Fluent software, the radon concentration distribution within the specified building was simulated after determining the necessary parameters. To validate the developed model, the numerical simulation results for specific points were compared with those obtained from analytical solutions and high-precision continuous radon detector measurements.

2. Experimental

2.1. Sample Building

This study investigates the effects of various physical factors on the distribution of radon concentration in the inside of a one-story building in Shandiz-Iran. This building is located at ground level and consists of three main areas: a salon, a kitchen with a bedroom, and an external toilet and bathroom separate from the main structure. The total area of the building is about 48 m^3 and the height of the roof is 3 m (Fig. 1).

The salon covers an area of approximately 24 m^2, with the building's entrance door located in the eastern corner of the southern wall. The door is 120 cm wide and 190 cm high, featuring a 4 cm gap along its width at the bottom, allowing for natural ventilation. The bedroom and the kitchen are similar in size with a length of 4 m and a width of 3 m parallel to the northern part of the building.

According to Fig. 1, both the bedroom and kitchen feature similar windows, each measuring 100 cm by 50 cm and situated 2 meters above the floor in the middle of their respective northern walls. The walls, roofs, and floors of the entire building are covered with tiles and ceramics with a low radon emission rate. On the other hand, there are some small but deep gaps in the walls. These gaps are the main source of radon entry to the building and are depicted in Fig. 1, Gap1 to Gap4.

2.2. Measuring chamber

To determine the radon emission rate from specific surfaces, a cubic measuring chamber was utilized. Except for its open face; the chamber's five other faces are coated with an impenetrable plastic material to prevent radon leakage. A Radon Meter device is placed inside the chamber to measure the output flux. The chamber dimensions are 45cm×45cm×25cm and with a measuring device inside the chamber, the volume of space is roughly .032 m^3. The area of open surface is 0.16 m^2.

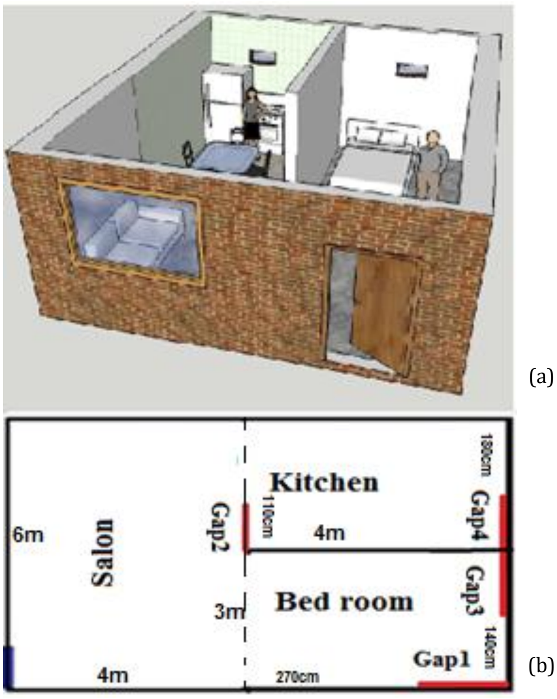


Fig. 1. 3D Model (a) and Sample Building Map (b).

2.3. Measuring device

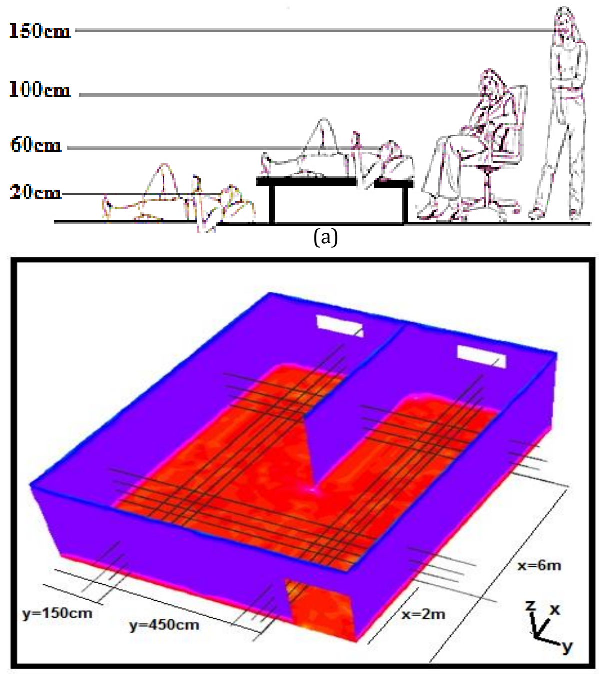
To measure the radon concentration in this study, we used the Radon Meter Model 2-1688 RTM manufacturedby the German company Sarad. It is a portable electronic measuring device that simultaneously measures and records pressure, temperature, relative humidity, and Thoron concentration. In addition, it can operate in two fast and slow modes (higher precision). The most important feature of this device is its rapid response to variations in radon concentration compared to other devices or other measuring methods.

3. Research theories

3.1. Method of Active Measurement

To focus our research on critical points affecting human health, we identified four significant heights from the floor, corresponding to typical breathing zones for adults with average stature (Fig. 2a) Radon concentration was measured at these heights for 16 sample points across different areas of the building (Fig. 2b) and compared with data obtained through Computational Fluid Dynamics (CFD) simulations.

At each measurement stage, data collection continued until a stable equilibrium state was achieved (equivalent to at least three half-lives of radon). Additionally, multiple boundary conditions used in the Fluent simulations—such as the interior temperatures of the walls, ceiling, and floor, along with the air pressure and temperature outside the building—were measured several times. The averages of these measured quantities were utilized in the study, and the relevant values are summarized in Table 1.



(b)

Fig. 2. Important respiratory heights for an adult human being with a normal stature (a) and a view of the 16 selected sample points that are located at the intersection of the drawing lines (b).

3.2. Method of Computational Fluid Dynamics (CFD)

Using the finite-volume method of conservation laws, numerical equations were solved by using powerful Fluent software. The general form of conservation laws in fluid flux for a small controlled volume, which depends on variable C is:

$$\frac{\partial(\rho C)}{\partial t} + \nabla.(\rho CV) = \nabla.(\rho D \nabla C) + S_C \qquad (1)$$

The first term on the left of this equation represents time rate of the variations of the fluid element C (unbalanced effect). The second term corresponds to the pure flux of the variable C moving out of the fluid element (motion effect), the first term on the right indicates the rate of C variation as a result of the diffusion, and finally, the last term is the source of C production, which shows the rate of flux change resulting from the C production.

Table 1. Quantities used in measurements and CFDs.

Symbols and Abbreviations			
κ	kenetic energy	E	Radon exhalation rate(Bq$m^{-2}s^{-1}$)
λ_V	Air change rate	K	Thermal Conductivity (w/m-k)
λ_{Rn}	Radon decay constant (s^{-1} or h^{-1})	G	Radon generation rate (Bq m^{-3} s^{-1})
C_p	Specific heat capacity (J kg^{-1} K^{-1})	ε	Turbulent dissipation rate (m^2 s^{-3})
ν	Kinematic viscosity (m2 s^{-1})	S	Source term
u	Velocity components in x, y, and z coordinates (m s^{-1})	V	Velocity vector(m/s)
v			
w			
A	Surface (m^2)	ρ	Density (kq/$m^{3)}$
M_W	Molecular weight(kmol/kg)	D_e	radon difference (Pa)
RH	Relative humidity	T	Temperature (·C)
C	Radon concentration (Bq m^{-3})	Δp	Pressure Deference (Pa)
L	Characteristic length(m)	V	Velocity (m/s)
ρ_s	Density of the soil grain	Re	Reynolds number
f	Radon emanation coefficient	A_{Ra}	Radium activity (Bq/kg)
CFD	Computational fluid dynamics	CRM	Continuous radon monitor
F_B	Body force vector	T	Temperature (K)
D	Effective diffusion coefficient (m^2s^{-1})	V	Volume (m^3)

All equations used in this method are derived from Eq. (1). The associated quantities are detailedin Table 1, and the equations used in this method are summarized in Table 2. Fluent software applies the laminar flow models to solve these equations. For calculations, are consideredadhesion forces in the areas adjacent tothe walls, and are accounted forin the areas remote from the walls, The use of unstructured gridsgovern the solutions of our equations. The advantage of using this type significantly reduces computational costs compared to structured grids Also, a corresponding coefficient was included to reduce the radon concentration across the entire building to correctly calculate the effect of reducing the radon concentration due to radioactive decay. It should also be noted that to simplify the numerical modeling, several limitations have been used in this research as the following:

1. The effect of the presence of residents and furniture in the building is neglected.
2. All gases in the building are assumed ideal.
3. Due to the lack of access to realistic changes in the temperature of the walls, floor, and ceiling during simulation, their average values are used as a constant.

3.3. Analytical solution method

A well-known analytical model was employed to estimate the radon concentration in the sample building. In this model, radon concentration increases by the release of radon through slabs and all surfaces in the building, conversely, the radionuclide decay and ventilation act to reduce. The final equation to determine the internal concentration of radon in a room with the volume V, is provided below [14-15].

$$C_i(t)=C_0e^{-\lambda t}+\frac{EA}{V\lambda}(1-e^{-\lambda t}) \tag{2}$$

where C_i is the internal radon concentration at time t (h), C_0 is the initial radon concentration at t = 0 in terms of Bqm^{-3}, $E(Bqm^{-2}h^{-1})$ is the radon input flux, or the radon emission rate from the soil and building materials, $A(m^2)$ is the area of the surface through which the radon gas is released, V(m^3) is the volume of the closed room or the test chamber and $\lambda(h^{-1})$ is the total radon decay rate that is given by the equation: $\lambda=\lambda_{Rn}+\lambda_V$

Table 2. Equations used in CFD for numerical solution.

Expression	Equation
$\frac{D(\rho)}{Dt}=\frac{\partial \rho}{\partial t}+\nabla.(\rho V)=$ $\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)+\frac{\partial}{\partial z}(\rho w)=0$	The mass conservation equation
$\nabla.(V)=\frac{\partial}{\partial x}(u)+\frac{\partial}{\partial y}(v)+\frac{\partial}{\partial z}(w)=0$	The mass conservation equation-in the steady state condition
$\frac{\rho D(V)}{Dt}=-\nabla P+\mu\nabla^2 V+F_B$	The momentum conservation equation
$\frac{\rho D(u)}{Dt}=\frac{\partial(\rho u)}{\partial t}+\nabla.(\rho uV)=$ $-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$ $\frac{\rho D(v)}{Dt}=\frac{\partial(\rho v)}{\partial t}+\nabla.(\rho vV)=$ $-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$ $\frac{\rho D(w)}{Dt}=\frac{\partial(\rho w)}{\partial t}+\nabla.(\rho wV)=$ $-\frac{\partial P}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g$	The simplified forms of the momentum equations -in the x, y and z directions.
$\frac{\partial(\rho C_p T)}{\partial t}+\nabla.(\rho C_p TV)=\nabla.(k\nabla T)+S_e$	The energy conservation equation
$\frac{\partial C}{\partial t}=\nabla.(D\nabla C)+\nabla.CV-\lambda_{Rn}C+G=0$	Conservation equation – In steady state and incompressible flow
$\frac{\partial(\rho C)}{\partial t}+\nabla.(\rho CV)=\nabla.(\rho D\nabla C)+S_C$	Radon transport equation
$\frac{\partial(\rho C)}{\partial t}+\nabla.(\rho CV)=\nabla.(\rho D\nabla C)$	Radon transport equation- no radon generation and decay in the air, SC= 0
$\nabla.(CV)=\nabla.(D\nabla C)$	Radon transport equation -For steady state conditions and constant radon density

4. Results and discussion

In two distinct time frames, namely March 2017 to January 2018 and July to September 2023, radon concentration were conductedat different points in the building in different periods. Based on these conditions, numerical solutions were performed both with Fluent software and with an analytical solution. Each complete cycle consisted at least 10 days without ventilationand 4 days under specific ventilation rates. following sections detail various surveys for a typical period.

4.1. Border conditions

All indoor air ventilation systems were completely sealed for approximately 10 days(860,000s). Although the outdoor air temperature fluctuated of around 10 °C in the air outside the building for a full day and night, the indoor wall temperatures remained relatively constant . According to our measurements, the average temperature of the northern, southern, eastern, and western walls, as well as the temperature of the ceiling and floor were recorded as 16, 17, 17, 19, 16, and 15 °C respectively.

4.2. Radon entrance rate

The floors and walls of the sample building were entirely insulated for this study, and aside from the four gaps in the floor—labeled as Gap1 to Gap4 in Fig. 1—the radon emission rate from all other surfaces was negligible. The radon emission rate of these gaps was measured for different months of the year, utilizing the previously described measuring chamber and continuous measuring device. By substituting all the necessary measured data into Eq. 2, the average values are presented in Table 3.

Table 3. Radon emission rates from slots.

/Gap Parameter	Gap1	Gap2	Gap3	Gap4
Location	Bed room	Hall	Bed room	Kitchen
Area(m^2)	4.9×10^{-2}	5.1×10^{-2}	3.2×10^{-2}	2.8×10^{-2}
E (Bq/m^2s)	0.48	0.64	0.42	0.39

4.3. Non-ventilation condition

Modeling of plates using CFD at x = 2 m and x = 6 m is illustrated in Fig. 3, based on the boundary conditions of the sample state and after 800,000 seconds of completely blocking all air ventilation routes. The intersection of these plates with the lines perpendicular to them at selected heights represents the density at the corresponding points.. The results of this simulation are compared with the data obtained from the measurement and are tabulated in Table 4. The maximum observed difference in these cases is approximately 15%, demonstrating a relatively good agreement between the CFD model and experimental results.

Also, Fig. 4 illustrates the contour variation of radon concentration at a height of 1.5 m from the floor under the same conditions. The average of these values and also the average of the data obtained from measurement are compared with the average concentration derived from the analytical solution of Eq. 3. The results, tabulated in Table 5, show that the experimental and analytical findings align well with the simulated results.

4.4. Effect of ventilation

To investigate the effect of ventilation on indoor radon concentration and its distribution, the gap beneath the main door and the windows on the northern walls were opened to allow fresh air to enter the building.The average temperature of the incoming air during this period was 14°C, and the radon concentration inside the building was negligible.During this period, meteorological data shows that for most of the time, the airflow direction outside the building was south-north. Therefore, during ventilation, it was assumed that fresh air entered the building through the gap beneath the main door and exited through the windows on the northern side.

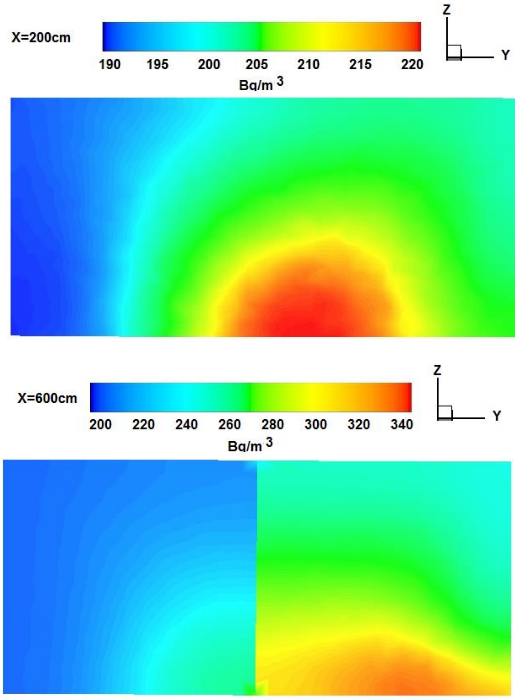


Fig. 3. Radon concentration contours in x=2 m and in x=6 m for a closed room mode.

Table 4. Radon concentration in 16 sample building samples based on numerical solution and measured in closed room mode.

	Coordinate(cm)			C(Bq/m^3)	
	X	Y	Z	Numerical	Measurement
1	200	150	20	199	228±31
2	200	150	60	196	219±28
3	200	150	100	195	202±23
4	200	150	150	194	187±19
5	200	450	20	215	241±37
6	200	450	60	211	229±24
7	200	450	100	208	221±22
8	200	450	150	206	211±21
9	600	150	20	227	241±27
10	600	150	60	221	244±25
11	600	150	100	218	237±21
12	600	150	150	214	234±27
13	600	450	20	334	385±39
14	600	450	60	316	341±29
15	600	450	100	296	317±32
16	600	450	150	274	294±27

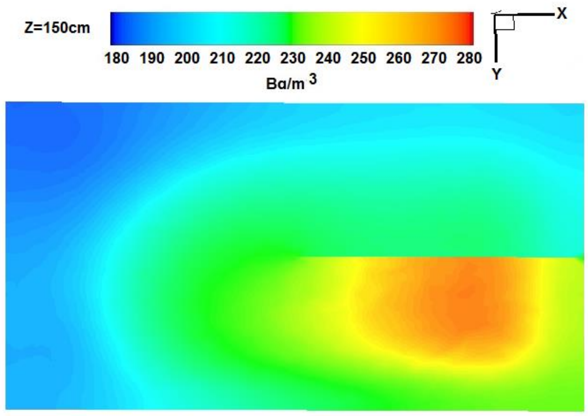


Fig. 4. Radon concentration contours at a height of 1.5 meters from the floor in non-ventilation conditions.

Table 5. Data obtained from measurement methods, analytical and numerical solutions for radon average concentration in the building after a 10-day period without ventilation.

Calculation Method	Analytical Solution	Numerical Solution	Measurement
C(Bq/m^3)	272±38	238	252±29

By incorporating the measured data from temperature variations into the corresponding thermodynamic equations, the air velocity and ventilation coefficients for each case were calculated individually.

These patterns show a mean velocity of approximately 40 mm /s in a typical period, for airflow from the main door. Also, the ventilation rate equivalent to this velocity, (according to the given air inlet and also the volume of the room) is $\lambda_V = 3.3\times10^{-5}\frac{1}{s}$.

Similar to the non-ventilated mode, the contours simulated for radon concentration using Fluent software at x=2 m and x=6 m were used to calculate radon concentration at these points. (Fig. 7)

The data obtained from this modeling , along the results from measurements conducted over a 4-day period (100,000s) following the start of the natural ventilation, is presented in Table 6. There is a good consistency between the results of modelling and those obtained from experimental data.

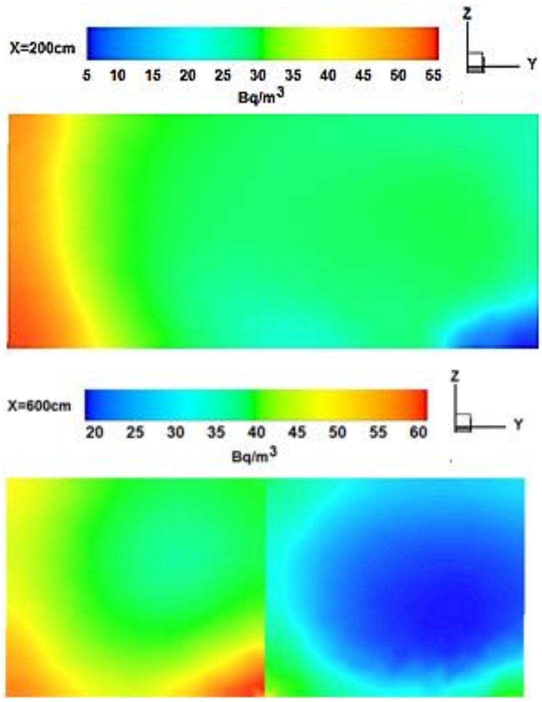


Fig. 5. Radon concentration contours at x = 2m and x = 6m for a 4 day period of continuous natural ventilation.

Table 6. Radon concentration in 16 sample points in the building based on numerical solution and measurement for a 4 day period of natural ventilation.

	Coordinate (cm)			C(Bq/m^3)	
	X	Y	Z	Numerical	Measurement
1	200	150	20	39.5	43±4
2	200	150	60	35.9	47±9
3	200	150	100	34.1	42±8
4	200	150	150	33.2	39±7
5	200	450	20	24.7	31±7
6	200	450	60	25.6	29±5
7	200	450	100	26.9	33±7
8	200	450	150	27.4	34±7
9	600	150	20	44.8	51±8
10	600	150	60	40.8	43±6
11	600	150	100	37.2	42±7
12	600	150	150	34.1	41±7
13	600	450	20	27.9	32±6
14	600	450	60	20.8	28±6
15	600	450	100	19.6	24±5
16	600	450	150	19.5	21±3

Also, Fig. 6 shows the radon concentration contour at a height of 1.5 meters from the floor after the same ventilation period, from which the mean value of radon concentration in the room can be obtained.Additionally, by inserting the ventilation coefficient in Eq. 5, the predicted analytical value at stable equilibrium was calculated. Our results are indicated in Table 7.

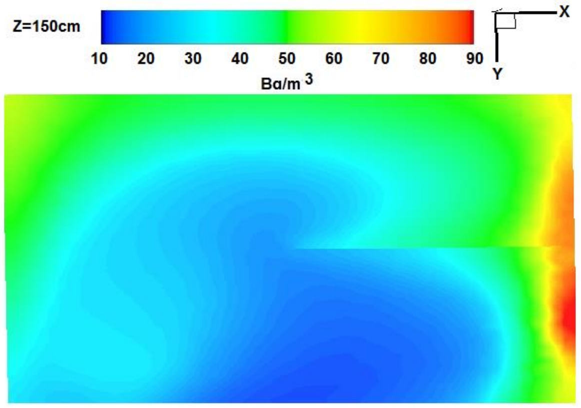


Fig. 6. Radon concentration contours at 1.5 meters height from the floor for a 4-day period of natural ventilation.

Table 7. Data obtained from measurement methods, analytical solution, and numerical solution for average radon concentration in the building for a 4-day period of natural ventilation.

Calculation Method	Analytical Solution	Numerical Solution	Measurement
C(Bq/m³)	17±2	16.1	23±4

4.5. Temperature effect

Fig. 7 (solid curve) shows the effect of temperature variations on radon concentration under natural ventilation conditions. As seen, the radon concentration decreases as the average temperature difference between the interior and exterior environments reduces. The results derived by other scientists (dashed curve) also confirm this behavior [13].

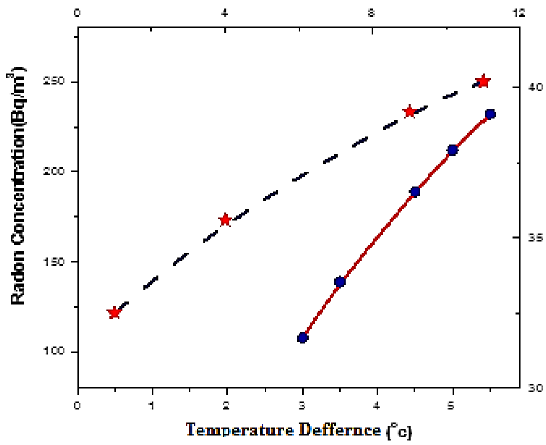


Fig. 7. The variations in radon concentration versus temperature differences between Internal and External Environments in Natural Ventilation, the solid curve is the current study, the dashed curve is Rabi et al. work, 2017.

4.6. Height effect

The accuracy of our results in this study demonstratesthat as height increases from the floor, the concentration of radon decreases. Fig. 8, shows a sample of these variations for the midpoint of the bedroom under natural ventilation condition in our research (solid curve) and also in other studies (dashed curve). An increase in the slope of these variations is observed with a decrease in heightin both distributions (Akbari and Oman, 2015) [11].

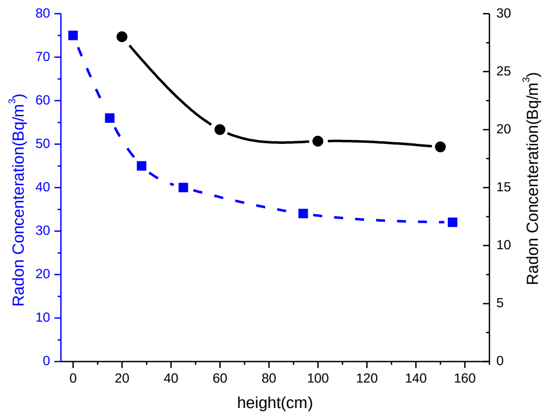


Fig. 8. The variation of radon concentration versus height difference from the floor in natural ventilation, the solid curve is Current study, dashed curve belongs to Akbari and Oman work.

5. Conclusion

In this paper, we used, a 3D model of CFD for research and development concerned with the distribution of radon concentration in a typical building. in the case where all the building's ventilation routes were closed for a 10-day period, the results obtained (Table 4) show that the maximum difference between the simulated and experimental data is approximately 16%.

On the other hand, the data indicatethat, although in all areas, radon concentrations are greater than the permissible value (100 Bq/m^3), a person sleeping on the ground or in a bed with their headin the middle of the bedroom receives a radiation dose nearly twice as high asthe person standing on the right side of the hall.

On the other hand, Table 5 shows that the average data obtained from these two exhibits a maximum discrepancy ofwith the results obtained from the numerical solutions under similar conditions. This indicates an acceptable accuracy for the simulated model.

Also, the data in Table 6 shows that although the results of numerical modeling and experimental data (after 4days of natural ventilation, assuming that fresh air entered the building from the gap under the main door, and exited from the windows on the northern side of the building)

There is a20-30%, discrepancy in 7 points out of 16 points, but a good consistency between the two methods observed for the remaining 9 points.

Further clarification of the data indicates that after the 4 days of natural ventilation, although the in all parts of the building is within permissible limits, but radon concentration at 20 cm high in the middle of the kitchen was about 142 percent more than the radon concentration in the place where one was standing in the middle of the bedroom.

Also, the average values of the numerical solution in natural ventilation are almost consistent with average values of the analytical solution. However,the average values of experimental data are about 35% higher than those of thenumerical solution (Table 7). There are three reasons for this discrepancy:

1. In the experimental averaging, only data at a height of 1.5 m and less were used, thus the absence of radon concentration data at higher altitudes leads to an increase inthe mean value.
2. In all calculations conducted in this paper, the release of radon from other areas of the building the release of radon from other areas of the building was ignoreddue to the low radon emission factors of those surfaces. However,the sum of these small quantities of radon released throughout the entire period is probably more significant, potentially affectingthe experimental measurements (as seen in most experimental data in Tables 4 and 6).
3. The presence of a background error of a few Bq/m^3b may lead to a larger error in measuring the lower radon concentration regions.

Also, as expected and shown in Fig. 7 (solid curve), radon concentration decreases with an increase in ventilation time, as well as by reducing the difference between indoor and outdoor temperatures, radon concentration reduces. In this regard, although the average air velocity during the natural ventilation period is assumed to be constant for simplicity, we know that this variable is reduced by decreasing the temperature difference between the two environments. This is also consistent with the results obtained by Rabi et al.

Furthermore, the results of this study show that radon concentration decreases by increasing altitude, and as shown in Fig. 8 (solid curve) it has the maximum gradient near the floor. It has also been reported by several different researchers, including Oman and colleagues, how to reduce radon concentration by increasing the height from the floor of the building. (Fig. 8 - dashed curve) [11,17-18].

Therefore, as it was said, using the CFD computations is a new way to estimate the distribution of radon concentration in a building and the general results of this research are consistentwith the results of other researchers in this subject, but the determination of four important breathing heights in a residential building (Fig. 2) and the central measuring and calculating the radon concentration for these points distinguishfrom previous researches in this field.

Finally, it should be acknowledged that due to the potential health risks posed by indoor radon, with the development of the necessary hardware and software, research is needed with the development of advanced hardware and software on the human body. Achieving more precise experimental measurements will enable us to find radon distribution models for each building in order to find the critical points where the radon concentration is considerable. Also, by using the results of these researches, buildings can be designed in such a way that their residents receive a lower annual effective dose.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work.

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