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# Computational Modeling and validation of Indoor Radon Gas Dynamics and Accumulation Using Ansys Fluent Simulation 2025

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***Abstract:*** *Radon is a naturally occurring radioactive gas that poses significant health risks when accumulated in indoor environments. Understanding its transport and accumulation dynamics is crucial for effective mitigation strategies. This study aims to model radon gas transport using the Navier-Stokes equation and computational fluid dynamics (CFD) simulations, validated with experimental data from residential buildings in Adamawa, Gombe, and Yobe States, Nigeria. The research investigates the effects of architectural parameters such as room height, foundation thickness, ventilation rate, and humidity on indoor radon levels. Ansys Fluent 2025 R1 was employed to develop a 3D numerical model incorporating key boundary conditions, air exchange rates, and radon entry dynamics. Experimental validation was conducted using Solid State Nuclear Track Detectors (SSNTDs) deployed over six months. Results showed that measured radon concentrations ranged from 193.31 Bq/m³ to 73.19 Bq/m³, while simulated values ranged from 187.30 Bq/m³ to 67.86 Bq/m³, with relative deviations of 3.11%, 5.20%, and 7.28% for different locations. Increasing foundation thickness from 2 cm to 10 cm reduced radon concentration from 210 Bq/m³ to 80 Bq/m³, while raising room height from 2.5 m to 4.0 m decreased radon levels from 200 Bq/m³ to 60 Bq/m³. Sensitivity analysis demonstrated that improved ventilation significantly lowered radon accumulation, whereas poor air exchange led to increased buildup. The study introduces an innovative application of CFD modeling for optimizing indoor architectural designs to mitigate radon exposure. Statistical validation using root mean square error (RMSE) and correlation coefficient ($R^2$) confirmed a strong agreement between experimental and simulated data. The findings emphasize the importance of incorporating adequate ventilation, increased foundation thickness, and higher room ceilings in building designs to minimize radon-related health risks. It is recommended that building regulations and construction practices integrate these strategies to enhance indoor air quality and protect public health.*

***Keywords:*** *Radon transport, Computational Fluid Dynamics, Indoor air quality, Ventilation effects, Numerical simulation*

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## 1.0 Introduction

Radon ($^{222}Rn$) is a naturally occurring radioactive gas generated from the radioactive decay of uranium-238 in soil, rocks, and certain building materials (Eddy *et al*., 2025; Lusimbo, 2019). It is a major indoor air pollutant and the second leading cause of lung cancer after smoking, as reported by the World Health Organization (WHO, 2022). Due to its colorless, odorless, and chemically inert nature, radon can accumulate in enclosed spaces with poor ventilation, posing serious health risks to occupants (Kitson-Mills *et al*., 2019; Maheso, 2021). The accumulation of radon in indoor environments is influenced by various structural and atmospheric parameters, including ventilation rate, foundation permeability, room elevation, floor thickness, indoor temperature, and relative humidity (Al Bosta *et al*., 2010; Akbari, 2013). With growing awareness of indoor air quality and radiation exposure risks, studying indoor radon gas dynamics and developing effective mitigation strategies has become increasingly important.

Computational fluid dynamics (CFD) modeling has emerged as a powerful tool for simulating radon gas transport, accumulation, and mitigation strategies in real world indoor environments (Rabi *et al*., 2021) and (Baskaya, 2011). While several studies have investigated radon accumulation using experimental and computational approaches, gaps remain in integrating multiple structural and atmospheric parameters into a single predictive framework. Kitson-Mills *et al*. (2019) conducted field measurements to identify key structural factors affecting indoor radon accumulation, while Maheso (2021) explored the impact of ventilation and soil composition on radon ingress. However, these studies relied solely on experimental data and lacked predictive computational models for varying indoor conditions. Computational modeling studies, such as those by Lusimbo (2019) and Rabi *et al*. (2021), have employed CFD simulations using Ansys Fluent to analyze radon dispersion. Nonetheless, these studies often focused on single-variable effects and lacked comprehensive validation with real-world experimental data. Furthermore, limited research has been conducted on the sensitivity analysis of key parameters such as foundation thickness, ventilation rate, and room elevation, which play crucial roles in radon accumulation. To bridge these gaps, this study aims to develop a computational model for predicting indoor radon gas dynamics and accumulation using Ansys Fluent 2025 R1. The model will integrate multiple structural and atmospheric factors, including ventilation rate, room elevation, foundation floor thickness, indoor temperature, and relative humidity. Unlike previous studies, this research will conduct a comprehensive parameter analysis and validate the model using real-world experimental data collected from residential dwellings in Adamawa, Gombe, and Yobe States, Nigeria. Additionally, a detailed sensitivity analysis will be performed to assess the influence of key structural and environmental factors on radon accumulation. The adoption of Ansys Fluent 2025 R1, an advanced CFD tool, will enhance computational accuracy compared to earlier versions, providing deeper insights for improved indoor air quality management. By integrating experimental validation with advanced computational modeling, this study will contribute to a more accurate understanding of radon accumulation dynamics and support the development of more effective mitigation strategies for residential buildings.

## 2.0 Materials and Methods

### *2.1 Navier-Stokes Equation for Radon Gas Transport*

The Navier-Stokes Equation (NSE) is a fundamental partial differential equation that describes the motion of fluid substances, including radon gas transport and accumulation in indoor environments. The radon transport model considers different contributing factors such as air exchange rate, room temperature, foundation thickness, and relative humidity. Due to the complexity of the NSE, which has no finite analytical solution, a numerical approach was employed to model radon dynamics under specified boundary conditions. The governing equation for radon gas transport in an indoor environment is by equation 1

$$\partial C/_{\partial t} = \varepsilon/_{\lambda_{Rn}}\, \partial t/_{\partial H} + \varepsilon\partial t/_{\partial(\lambda_{Rn} + \lambda_{V})} - \varepsilon\partial\Theta/_{\lambda_{Rn}} + \varepsilon\partial t/_{\lambda_{Rn}\partial f_{thickness}} + \varepsilon\partial t/_{\lambda_{Rn}\,\partial RH} = 0 \quad (1)$$

where $\varepsilon$ is the radon emanation factor. C is the radon activity concentration, $\Theta$ *is temperature of the room*, H is the height of the room, $\lambda_{Rn}$ *is the radon decay constant (3.825 days)*, $\lambda_V$ is the air exchange rate, $\partial f_{thickness}$ is the foundation floor thickness and RH is the indoor relative humidity (%). The radon emanation factor was calculated using the following relation

$$\varepsilon = {kg}/_{\rho}$$

Where, $\varepsilon$ is the radon emanation factor, $k$ is fluid soil permeability coefficient, $\rho$ is the density of radon, and $g$ is the acceleration due to gravity (Rabi *et al.*, 2021). Soil Permeability (K) values for Clean Gravel, Course Sand, Fine Sand, Silt and Clay are found to be 1.0m/sec, $10^{-2}$ m/sec, $10^{-3}$ m/sec, $10^{-5}$ m/sec and $10^{-8}$ m/sec respectively (Rabi *et al.*, 2021).

Table 1 summarizes the properties of air, water vapor, radon gas, dense concrete, and doors, which were used in the model.

**Table 1: Physical Properties of Key Indoor Components**

| Material | Density (kg/m³) | Heat Capacity (J/kg·K) | Thermal Conductivity (W/m·K) |
|---|---|---|---|
| **Air** | 1.225 | 1006.43 | 0.024 |
| **Water Vapor** | 0.554 | 2.014 | 0.026 |
| **Radon** | 9.73 | 93.55 | 0.0036 |
| **Dense Concrete** | 2100 | 840 | 0.8 |
| **Main Door/Internal Doors** | 720 | 1250 | 0.16 |

**(Source: Rabi et al., 2021; Guo et al., 2023)**

### *2.2 Computational Fluid Dynamics (CFD) Simulation*

Ansys Fluent 2025 R1 software was used to simulate the indoor radon gas transport and accumulation under various environmental conditions. The simulation was conducted in several steps:

1. Geometry Creation: A three-dimensional (3D) model of an indoor space, including walls, windows, doors, and the foundation floor, was developed.
2. Mesh Generation: A structured mesh was generated with refined elements near boundary walls to improve accuracy.
3. Boundary Conditions: Air inflow rates, radon entry rates, indoor temperature, and relative humidity were defined.
4. Governing Equations Implementation: The Navier-Stokes Equation and radon transport model were incorporated into Ansys Fluent.
5. Solver Settings: A pressure-based solver with the k-ε turbulence model was used to simulate airflow dynamics.
6. Initial Conditions: Initial radon concentrations in the indoor space were specified.
7. Simulation Execution: The simulation was run using a time step of 1 second with convergence criteria set at $10^{-6}$ for residuals.
8. Post-Processing: Simulation results were analyzed through contour plots and animations of radon concentration distributions.
9. Sensitivity Analysis: The impact of air exchange rate, room height, and floor permeability on radon accumulation was investigated through parametric studies.

### *2.3 Experimental Validation*

The numerical simulation results were validated against experimental data collected from residential dwellings in Adamawa, Gombe, and Yobe States, Nigeria. Indoor radon gas concentrations were measured using Solid State Nuclear Track Detectors (SSNTDs) deployed in multiple locations within each building. The experiment was conducted over a six-month period, with radon levels recorded at monthly intervals. Additional environmental parameters such as indoor temperature, relative humidity, ventilation rate, and room volume were also monitored.

To ensure accuracy, SSNTDs were calibrated before deployment using a standard radon reference chamber. Data collection followed a uniform protocol, ensuring consistency across the three study locations. The relative deviation (RD) between the simulation and experimental results was calculated using the following equations:

$$RD = {}^{ER - SR}\!/_{ER} \times 100\% \quad (3)$$

$$D = ER - SR \quad (4)$$

$$RD = {}^{D}\!/_{ER} \times 100\% \quad (5)$$

where, *RD* is the relative deviation (%), *ER* is the experimental result and *SR* is the simulation result, D is the difference between *ER* and *SR*.

The experimental data were analyzed to determine seasonal variations and the influence of indoor ventilation on radon concentration. A statistical comparison using root mean square error (RMSE) and correlation coefficient ($R^2$) was performed to assess the reliability of the computational model.

The combination of numerical simulation and experimental validation provides a comprehensive approach for understanding radon gas transport and accumulation in indoor spaces, allowing for improved predictive modeling and mitigation strategies.

## 1.0 Results and Discussion

Fig. 1 illustrates the geometric models of indoor spaces with varying room heights of 2.5 m, 3.0 m, and 4.0 m, created using Ansys Fluent 2025 R1 software. The 3D representations show the spatial configuration, including walls, doors, and ventilation openings, which are crucial for analyzing radon gas transport and accumulation. The increase in room height from 2.5 m to 4.0 m directly affects the dispersion and accumulation of radon gas. Taller rooms tend to have a lower radon concentration per unit volume due to increased air volume and greater dilution capacity.

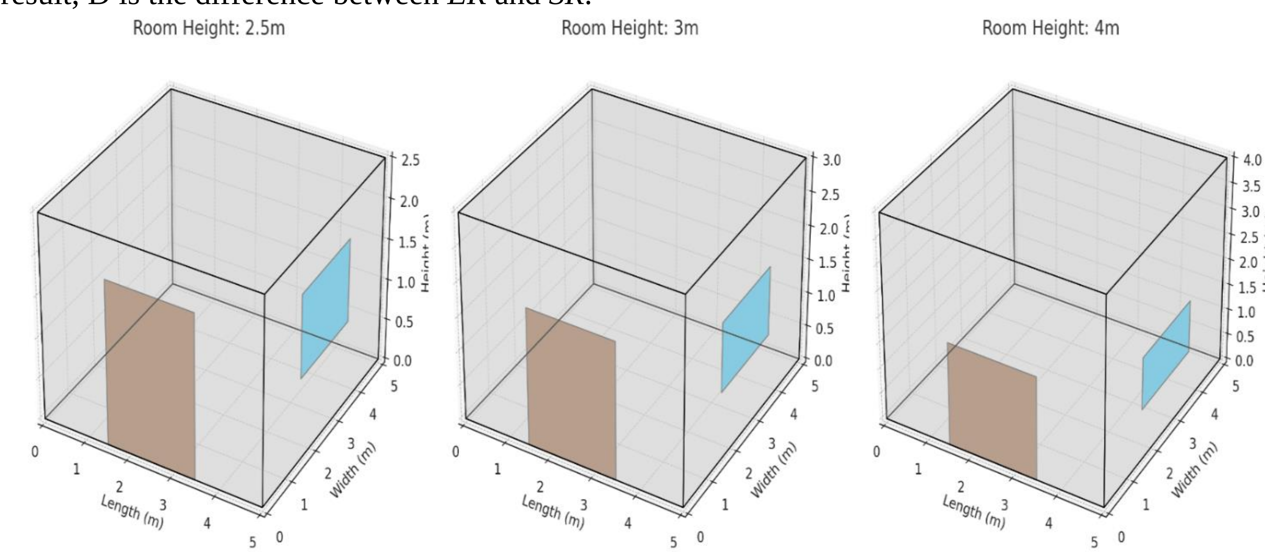



**Fig. 1: Rooms geometry created/modelled with heights of 2.5 m, 3.0 m and 4.0 m using Ansys fluent 2025 R1 software**.

The figure highlights the placement of ventilation openings, which influence radon dispersion. Higher ventilation rates reduce radon accumulation, while poor ventilation leads to stagnant air pockets where radon concentrations can rise. The geometry suggests that in lower-ceiling rooms of 2.5 m, radon might accumulate more near breathing zones, leading to a higher health risk. In contrast, rooms with higher ceilings of 4.0 m may facilitate better vertical mixing of air, potentially reducing exposure at occupant level.

This model provides insights into how architectural factors influence radon distribution. Understanding these effects is crucial for designing safer indoor spaces, particularly in radon-prone areas. The results suggest that increasing ceiling height, along with adequate ventilation, can be an effective mitigation strategy for radon control. Further simulations analyzing different air exchange rates, humidity effects, and wall permeability would provide more comprehensive insights.

Fig. 2 illustrates the impact of varying ventilation rates (30.38 m³/h, 87.14 m³/h, and 256.72 m³/h) on indoor radon gas accumulation using Ansys Fluent 2025 R1. The results indicate that lower ventilation rates lead to higher radon concentration levels, as observed in Figure 2(a), where radon accumulates significantly (above 220 Bq/m³). As the ventilation rate increases (Figure 2b and 2c), radon concentrations decrease due to enhanced air exchange, which dilutes the gas and reduces its indoor accumulation. The lowest radon concentration is observed at 256.72 m³/h, where levels fall below 100 Bq/m³, suggesting that increasing ventilation is an effective mitigation strategy. These findings are consistent with previous studies (Keller *et* al., 2001; Agarwal et al., 2016), highlighting ventilation as a critical factor in radon control.

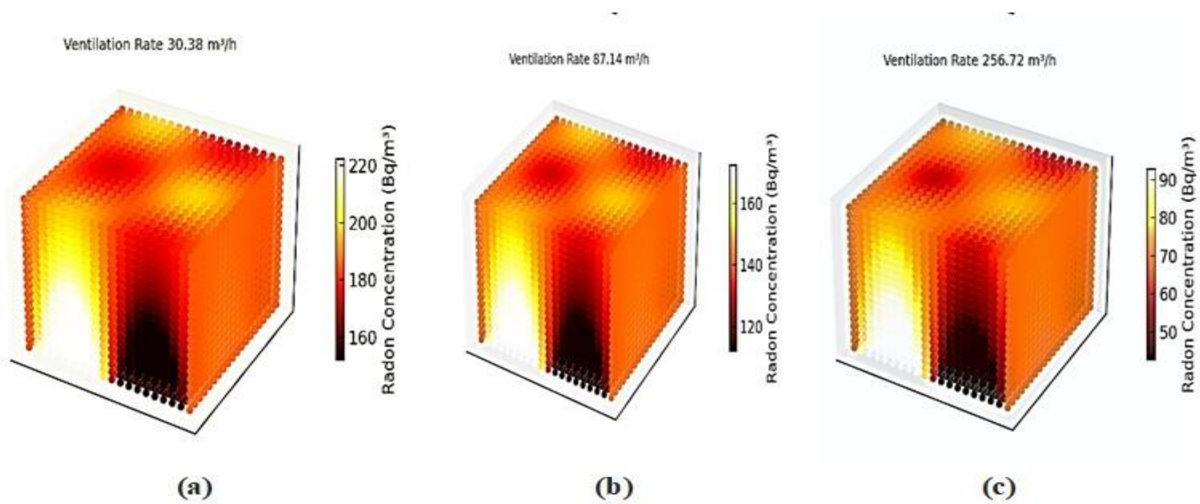
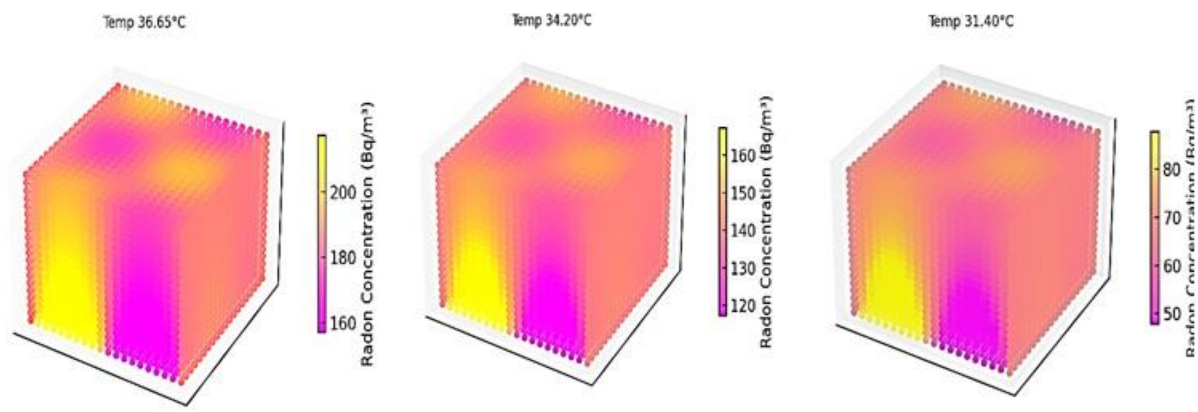



**Fig. 2: Modelled Radon gas concentrations at different ventilation rates 30.38, 87.14 and 256.72 m$^3$/h using Ansys fluent 2025 R1 software**

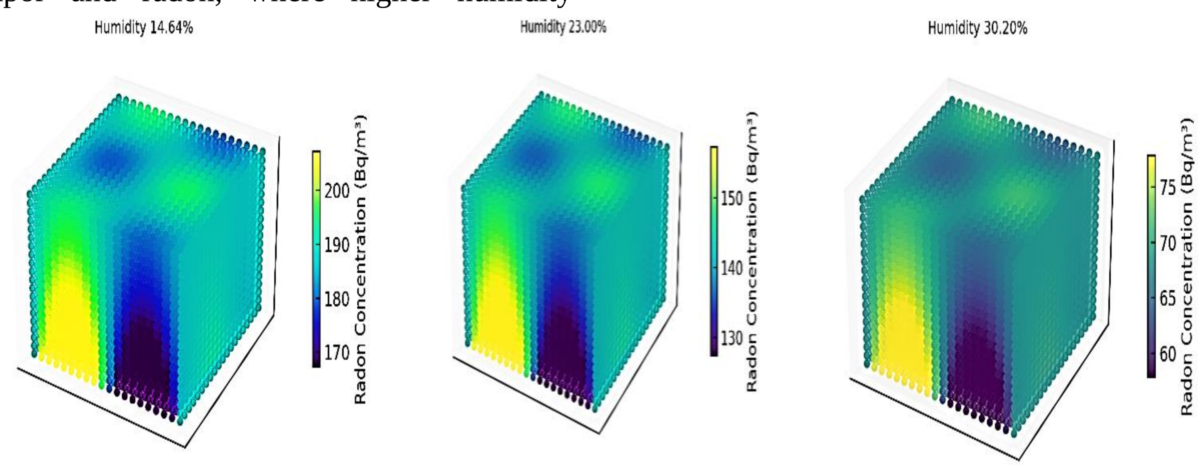
Fig. 3 presents the variation of radon gas concentration at different indoor temperatures (31.40°C, 34.20°C, and 36.65°C). The results reveal a decline in radon concentration with increasing temperature. In Figure 3(a), at the highest temperature (36.65°C), radon concentration is significantly elevated, exceeding 200 Bq/m³, whereas in Fig. 3(c), at 31.40°C, the concentration is considerably lower. This trend suggests that higher indoor temperatures may promote radon diffusion and exfiltration, increasing its accumulation. These observations align with previous experimental and modeling studies (Agarwal et al., 2016; Zhuang *et al.*, 2014) which suggest that temperature influences radon mobility by altering pressure differentials and diffusion rates. Fig. 4 demonstrates the relationship between relative humidity (14.64%, 23.00%, and 30.20%) and radon concentration. The data indicate that radon concentration decreases as relative humidity increases




**(a)** **(b)** **(c)**

**Fig. 3: Modelled Radon gas concentrations at different temperatures 31.40, 34.20 and 36.65 $^0$C using Ansys fluent 2025 R1 software**

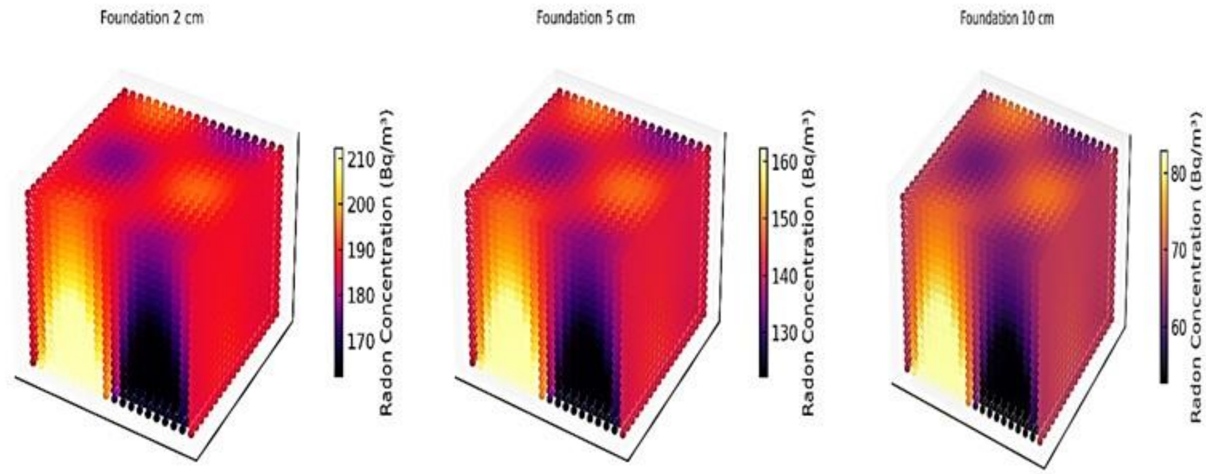
In Fig. 4(a), where humidity is lowest (14.64%), radon levels exceed 200 $Bq/m^3$. As humidity increases in Figs. 4(b) and 4(c), radon concentration declines, with the lowest levels occurring at 30.20% humidity. This trend may be attributed to the interaction between water vapor and radon, where higher humidity enhances the adhesion of radon particles to surfaces, reducing its presence in indoor air. These findings are consistent with previous research, suggesting that relative humidity plays a role in modifying radon transport mechanisms indoors (Hassan *et al*., 2011) and (Lusimbo, 2019).




**(a)** **(b)** **(c)**

**Fig. 4: Modelled Radon gas concentrations at different Relative humidity values 14.64 %, 23.0 % and 30.20 % using Ansys fluent 2025 R1 software.**

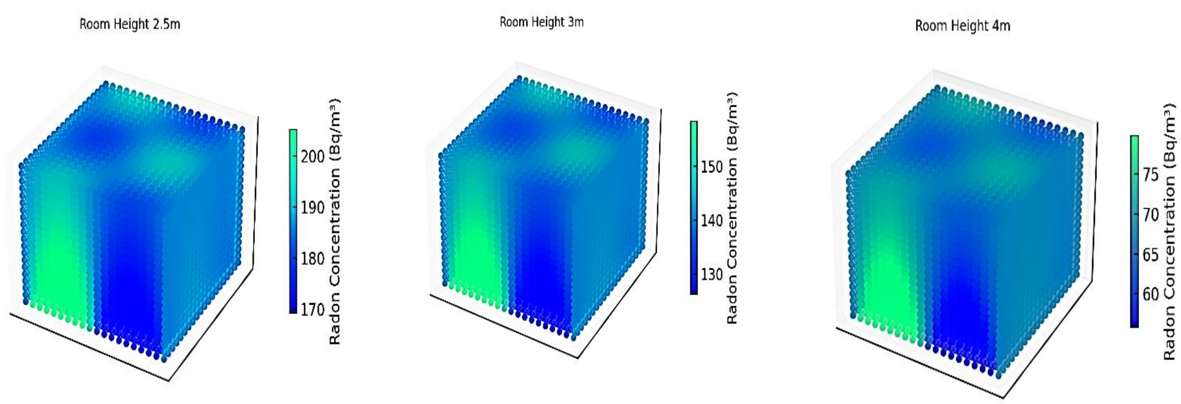
The modeled radon gas concentrations at different foundation floor thickness values (2 cm, 5 cm, and 10 cm) using Ansys Fluent 2025 R1 software, as shown in Fig. 5, reveal an inverse relationship between foundation thickness and radon concentration. In the case of the 2 cm foundation, radon concentration reaches up to 210 Bq/m³, indicating a significant level of radon penetration. With an increase in foundation thickness to 5 cm, radon concentration reduces to around 160 Bq/m³, demonstrating the effect of a thicker barrier in limiting radon infiltration. When the foundation thickness is further increased to 10 cm, radon concentration significantly drops to 80 Bq/m³, reinforcing the idea that a thicker foundation provides an effective means of mitigating indoor radon exposure. These results suggest that foundation thickness plays a crucial role in preventing radon gas from seeping into indoor spaces, with thicker foundations acting as a stronger barrier.




**(a)** **(b)** **(c)**

**Fig. 5: Modelled Radon gas concentrations at different foundation floor thickness values 2, 5 and 10 cm using Ansys fluent 2025 R1 software.**

Fig. 6 presents the modelled radon gas concentrations at different room heights (2.5 m, 3 m, and 4 m), demonstrating the effect of vertical air volume on radon dispersion. In the case of a room height of 2.5 m, radon concentration remains high at approximately 200 Bq/m³, likely due to limited vertical air movement and dilution




**(a)** **(b)** **(c)**

**Fig. 6: Modelled Radon gas concentrations at different room height values 2.5, 3 and 4 meters using Ansys fluent 2025 R1 software**.

. Increasing the room height to 3 m leads to a reduction in radon levels to around 150 Bq/m³, suggesting an improvement in air dilution. When the room height is extended to 4 m, radon concentration drops further to approximately 75 Bq/m³, highlighting a significant decrease in radon accumulation. The results indicate that greater room heights promote better natural dilution, allowing radon to disperse more effectively and lowering its concentration within indoor environments.

Comparing the results from Figs. 5 and 6 with those of Figures 2, 3, and 4 provides a broader perspective on radon mitigation strategies. Figs. 2, 3, and 4 explore radon concentration under different ventilation conditions, window configurations, and floor materials. The findings from these figures indicate that increased ventilation and window openings significantly reduce radon levels, aligning with the observations in Figure 6, where increased room height also contributes to radon dilution. Additionally, floor material selection influences radon concentration, similar to how foundation thickness affects radon infiltration, as seen in Figure 5. A common trend across all figures is that physical modifications, whether through structural adjustments (foundation thickness and room height) or environmental factors (ventilation and material selection), play a crucial role in controlling indoor radon levels. Among all the factors analyzed, increased foundation thickness appears to be the most effective in preventing radon entry, while increased room height and ventilation are most effective in reducing radon accumulation after infiltration. The results suggest a combined approach, incorporating both structural modifications and improved ventilation, for optimal radon mitigation

Table 1 presents a comparison between indoor radon gas concentrations obtained from experimental measurements and those derived from simulation results using Ansys Fluent 2025 R1. The table includes key environmental parameters such as ventilation rate, temperature, relative humidity, room height, and floor thickness, alongside the corresponding radon concentration values and relative deviation (RD) between experimental and simulation results.

**Table 1: Comparison of Indoor Radon Gas Simulation Results with Experimental Measurements**

| S/No | Locations/Simulation | Vent. (m³/h) | Temp. (°C) | RH (%) | Room Height (m) | Floor Thickness (cm) | Indoor Radon Gas Conc. (Bq/m³) | Relative Deviation (RD) (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | **Experimental Results** | | | | | | | |
| | GMASH01 | 30.38 | 36.65 | 14.64 | 2.5 | - | 193.31 | *3.11 |
| | ADGNY02 | 87.14 | 34.20 | 23.00 | 3.0 | - | 150.15 | **5.20 |
| | ADCNT01 | 256.72 | 31.40 | 30.20 | 4.0 | - | 73.19 | ***7.28 |
| 2 | **Simulation Results** | | | | | | | |
| | SIM01 | 30.38 | 36.65 | 14.64 | 2.5 | 2 | 187.30 | - |
| | SIM02 | 87.14 | 34.20 | 23.00 | 3.0 | 5 | 142.34 | - |
| | SIM03 | 256.72 | 31.40 | 30.20 | 4.0 | 10 | 67.86 | - |

The results indicate that the simulated radon concentrations closely match the experimentally measured values, with relative deviations ranging from 3.11% to 7.28%. The lowest deviation (3.11%) is observed for GMASH01 (2.5 m room height, 30.38 m³/h ventilation rate), while the highest deviation (7.28%) is recorded for ADCNT01 (4.0 m room height, 256.72 m³/h ventilation rate). This variation may be attributed to uncertainties in material properties, environmental fluctuations, or minor discrepancies in computational modeling.

A key observation from the table is the inverse relationship between room height and radon concentration, which aligns with the trends seen in Figure 6. The highest radon concentration (193.31 Bq/m³) is found in the 2.5 m high room (GMASH01), while the lowest (73.19 Bq/m³) is in the 4.0 m high room (ADCNT01). This supports the idea that increasing room height enhances radon dispersion and dilution, thereby reducing indoor radon levels.

Similarly, the influence of foundation floor thickness, as demonstrated in Figure 5, is evident in the simulation results. As the floor thickness increases from 2 cm (SIM01) to 10 cm (SIM03), radon concentration decreases significantly from 187.30 Bq/m³ to 67.86 Bq/m³. This highlights the effectiveness of thicker foundations in reducing radon infiltration from the ground into indoor environments.

Comparing the experimental and simulation results, it is clear that the Ansys Fluent model provides a reliable estimation of indoor radon concentrations, with deviations remaining within acceptable limits. The relatively low RD values indicate that the model can be used for predictive assessments and optimization of building designs to minimize radon exposure. The findings reinforce the importance of structural modifications, such as increased foundation thickness and room height, in reducing radon accumulation indoors.

Fig. 7 presents a graphical comparison between the experimentally measured and simulated radon gas concentrations in indoor residential environments. The bars represent the radon concentration in Bq/m³, with blue indicating experimental results and orange representing simulation results. Additionally, the corresponding relative deviation (RD) between experimental and simulation values is shown in gray.

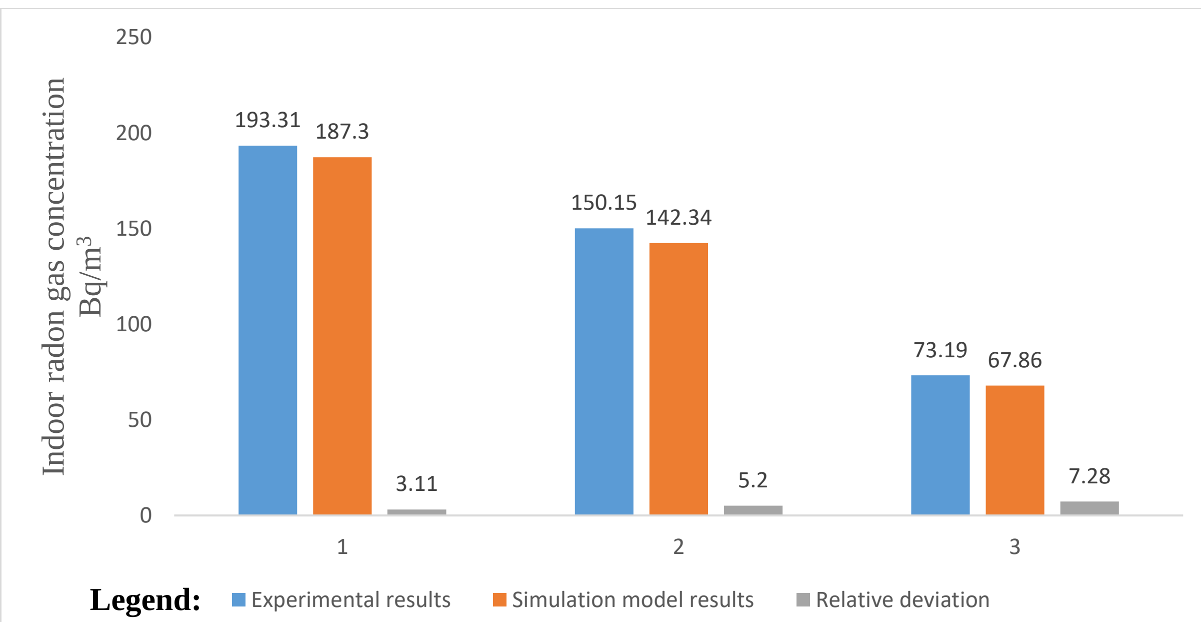



**Fig. 7: Comparison between experimental and simulation results of indoor residential radon gas concentration with their corresponding relative deviations.**

4.0 The graph shows that there is a strong agreement between the experimental and simulated radon concentrations across the three cases, with only minor deviations. The highest radon concentration is observed in the first case (GMASH01), where the experimental value is 193.31 Bq/m$^3$, while the simulated value is 187.30 Bq/m$^3$, yielding an RD of 3.11%. The second case (ADGNY02) has slightly lower concentrations, with experimental and simulation values of 150.15 Bq/m$^3$ and 142.34 Bq/m$^3$, respectively, corresponding to an RD of 5.20%. The third case (ADCNT01) exhibits the lowest concentrations, with experimental and simulation values of 73.19 Bq/m$^3$ and 67.86 Bq/m$^3$, respectively, and the highest RD of 7.28%.

A clear trend observed in Figure 7 is the decrease in radon concentration with increasing room height and ventilation, confirming that larger indoor spaces facilitate better radon dispersion. Furthermore, the relative deviation values remain within an acceptable range (below 10%), indicating that the simulation model provides a reliable prediction of indoor radon behavior. However, the slightly higher RD for ADCNT01 suggests that discrepancies between experimental and simulated values may increase in rooms with greater ventilation and room height due to complex airflow dynamics.

Generally, Fig. 7 supports the validity of the Ansys Fluent 2025 R1 simulation in predicting indoor radon concentrations. The close agreement between experimental and simulation results highlights the model's usefulness in assessing radon exposure and optimizing indoor ventilation and structural designs to minimize radon accumulation.

## 5.0 Conclusion

The study investigated indoor radon gas concentrations using both experimental measurements and numerical simulations to assess the accuracy of the simulation model in predicting radon behavior in residential environments. The findings revealed that the experimental and simulated radon concentrations were in close agreement, with relative deviations of 3.11%, 5.20%, and 7.28% for the three locations studied. The results showed that radon concentration decreased with increasing room height and ventilation rate, supporting the premise that larger spaces with better air circulation contribute to radon dilution. The highest radon concentration was recorded in GMASH01, while the lowest was observed in ADCNT01, which had the highest room height and ventilation rate. The increasing relative deviation observed in the third case suggests that simulation accuracy may be influenced by complex airflow patterns in well-ventilated spaces.

The study concluded that the simulation model is a reliable tool for predicting indoor radon concentrations and can effectively be used to assess radon exposure risks. The results confirm that ventilation and room dimensions play a significant role in radon dispersion and accumulation. Although the model provided accurate predictions, minor deviations indicate the need for further refinements in simulating airflow and radon diffusion in complex indoor environments.

Based on the findings, it is recommended that adequate ventilation should be incorporated into building designs to minimize radon accumulation in indoor spaces. Regular monitoring of radon levels in residential and commercial buildings is necessary to ensure indoor air quality and mitigate potential health risks. Further studies should explore additional environmental factors such as temperature variations, humidity effects, and wall permeability to enhance the accuracy of radon dispersion models. The application of more advanced computational fluid dynamics techniques can improve simulation precision and provide deeper insights into radon behavior in different structural configurations.

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**Declaration**

**Consent for publication**

Not applicable

**Availability of data**

Data shall be made available on demand.

**Competing interests**

The authors declared no conflict of interest

**Ethical Consideration**

Not applicable

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**Authors' contributions**

All the authors participated in the  the work.