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Analysis of Indoor Radon Distribution Within a Room By Means of Computational Fluid Dynamics (CFD) Simulation

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ABSTRACT

Radon gas is recognized by international organizations such as the United States Environmental Protection Agency (US-EPA) as the main contributor of radiation environmental to which human beings are exposed. Therefore, the evaluation of indoor radon concentration is a matter of public interest. The emanation and the income of the gas inside a room will generate a negative impact on the quality of the air when the place is not properly ventilated. Understanding how this gas will be distributed inside the room will allow to predict the spatial and temporal variations of radon levels and identify these parameters will provide important information that researchers can be used for calculate radiation dose exposure. Consequently, this studies can prevent a health risk for the people that live or work within the room. Currently, several researchers use the technique called Computational Fluid Dynamics (CFD) to simulate the distribution of gas radon, making use of the various commercial programs that exist in the market. In this work, three simulations were developed in rooms that have a similar geometry but different dimensions, in order to observe how the gas is distributed inside a closed space and to analyze how this distribution varies when the volume of the place is increased. The results show that as the volume of the site increases the radon is mitigated more rapidly and therefore has lower levels of concentration of this gas, as long as the level of radon emanation is kept constant.

1. Introduction

Radon is a radioactive element that is produced from the decay of uranium-235, uranium-238 and thorium-232, elements that are naturally found in the subsoil distributed throughout the planet [1]. Rn-222 is the most abundant of radon isotopes and is presented as a colorless, odorless and tasteless gas. Its diffusion coefficient in air is 1×10^{-1} cm^2/s and in water it is 1.13×10^{-5} cm^2/s [2]. The concentration of radon in a given place can vary due to various factors, such as the rainy season and the occurrence of telluric movements.

The danger of this radioactive gas for human health is generated for the following reason: if the alpha particles, emitted by the isotope, are inhaled by a person, they can get trapped in their lungs, while these particles disintegrate, small explosions of energy are released. causing damage to the tissues of the lungs. If this process continues indefinitely, as the years go by, cancer can be generated in this organ [3]. For this reason, it is necessary to measure it in all enclosed spaces where people live or work [4-9] and mitigate it when their levels exceed the limits established by the different international organizations (148 Bq/m^3 for homes and 400 Bq/m^3 for places of work [10]). An advantage of radon for mitigation is that it can be adsorbed by a wide variety of solids, such as activated carbon and gels, this advantage is due to the ease it has to condense [11].

In addition to the measurement of intramural radon, it is very important to understand its emanation and distribution [12-15] in order to be able to predict the spatial and temporal variations of the level of its presence within a room, in this way it is possible to calculate the dose at which will be exposed a person who works or lives within this place. For this reason, understanding, prediction and measurement are essential for proper radiological protection.

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To understand this distribution, it is necessary to analyze the flow of fluid, the air conditions and the effects of the gas inside the place, for this reason the equations of the conservation of energy, mass and movement in the field must be defined of the flow [16-20]. The resulting governing equations are differential equations in partial derivatives (PDE) that include several independent variables.

There are different ways to solve these equations, one of them is the numerical solution by simulating computational fluid dynamics (CFD). The CFD technique is designed to convert continuous equations to discrete or algebraic equations based on different methods of discretization.

There are different approaches to solve PDE. One of these approaches is the numerical solution using CFD. The CFD code is designed to solve PDE numerically. CFD codes convert PDE from continuous equations to discrete equations (algebraic equations) based on different methods of discretization. In fluid dynamics, the main methods of discretization are the finite volume method (FVM), the finite difference method (FDM) and the finite element method (FEM). Unlike the analytical solution, which solves the equations for all points in the domain, the numerical methods only admit discrete points (nodes) and the values are calculated at discrete locations in a mesh geometry. The creation of geometry and mesh is the first step of preprocessing in numerical modeling.

The FDM method uses the differential forms of the guiding equations and applies the expansion of the local Taylor series to approximate the differential equations, while the FVM method and the FEM use the integral form of the guiding equations. The FEM method divides complicated equations into small elements that can solve each other. There are two advantages to using the FVM method with respect to the FEM: the first is that FEM requires more computer memory compared to the other method, the second is that it can be used with unstructured meshes. In the FVM method, the computational domain is divided into small volumes, and variables such as speed and temperature are placed at the centroid of the control volume instead of placing them at the nodal points. Then, the values of the field variables in the vertices are obtained by interpolation and then, the volume integrals become surface integrals using the divergence theorem. These terms are calculated as flows through the volume surfaces of each finite volume, because the flow entering a given volume is identical to that left by the adjacent volume. These methods are called conservatives. One of the most powerful and precise computer programs that exist to solve problems in the area of physics and engineering that involve fluid flow is ANSYS MULTIPHYSICS.

This work aims to determine how radon gas is distributed within a room as the gas emanates from the ground. It is evident that there are multiple variables that can be modified to observe how the gas is distributed within a space, such as the dimensions of the place, the geometry of the room, the number of accesses that the room presents (doors, windows, access from the ceiling), the air flow, the radon concentration level that emanates from the ground, the air features, the room temperature, etc. For this reason, in this work only the dimensions of the room will be varied. First a simulation will be developed in a room that has a volume of 30 m^3, then another simulation in a room that has a volume of 100 m^3 and finally another simulation in a room with 200 m^3 of volume. Subsequently, the results will be analyzed and it will be determined how radon is distributed within the room and how this distribution is modified as its dimensions increase. For the development of these simulations, the fluid flow module (Fluent) will be used, which is inside the ANSYS software package.

2. Methodology

The steps taken to develop the three simulations were the following:

1) The first step was to decide the specific characteristics that the rooms would tend to develop the analysis of the radon distribution as it emanated from the floor of the room. It was decided to build a completely enclosed room with a small access on the roof. In this way the room would simulate a basement or a wine cellar.
2) The Design Modeler module in ANSYS was used to build the first room. This first room has dimensions of 3.11 long, 3.11 wide and 3.11 m high to obtain a total volume of 30 m^3. The access to the room has dimensions of 0.6 long, 0.6 wide and 0.01 m thick. The distance between the entrance to the room and the wall of the x axis is 0.5 m and the y axis is also 0.5 m. Figure 1 presents the room designed to develop the first simulation.
3) The next step was to construct the meshing of this geometry, that is, to divide the figure into nodes so that the program can perform the corresponding calculations. Mesh construction was developed in the Mesh module of the program.
4) After choosing the most optimal parameters to construct the mesh, the functions that each face of the geometric figure would develop were selected. The base of the figure was configured for radon gas to emanate from this area (3.11x3.11 m). The smallest geometric figure (whose dimensions are 0.6x0.6 m) was configured to allow the entry of air from outside the room. All other faces in the figure were configured as air and gas boundary zones (physical walls). Finally, the entire volume within the geometric figure (30 m^3) was

configured to allow free flow of radon gas and air. These configurations were also developed in the mesh module of the program.

5) Subsequently, the simulation of the radon expansion in the fluid flow (Fluent) module of the software was developed, choosing the most optimal parameters to obtain reliable results. Various parameters selected in the module will not be mentioned because they belong to the input conditions that software requires to develop the simulation correctly. But the parameters that can be mentioned because they refer to variables that would be observed in a real environment are presented in Table 1 and Table 2.
6) After entering the parameters required by the program, the simulation was executed.
7) Subsequently, the simulation results were observed and analyzed in the environment called post-processing within the fluid flow module.
8) After obtaining the results of the simulation of the radon expansion for the room with a volume of 30 m^3, the same steps were performed for the simulations of the other two rooms (100 and 200 m^3). Even the same dimensions and position of the access door were maintained. The only variable that was modified was the length, width and height of the rooms. For the second room (100 m^3) the following dimensions were chosen: 4.65 long, 4.65 wide and 4.65 m high. And for the third room (200 m^3) the following dimensions: 5.85 long, 5.85 wide and 5.85 m high.

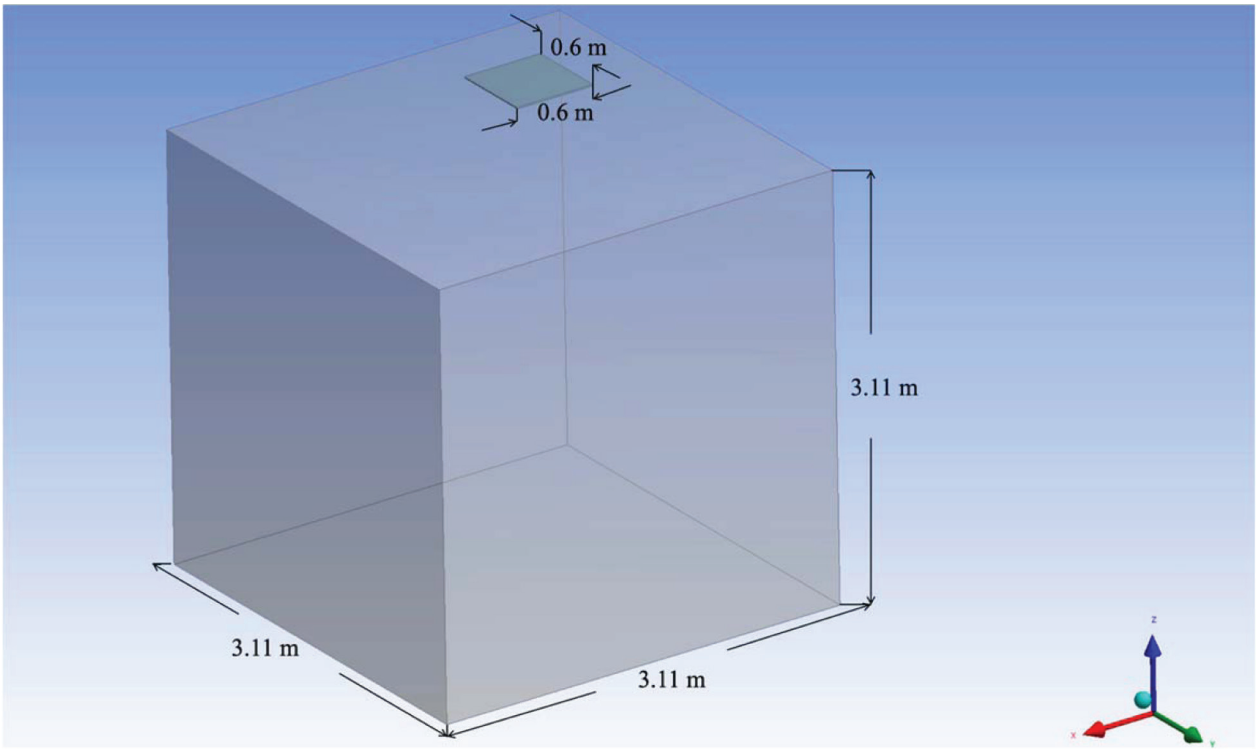

Figure 1: Room designed to develop the first simulation (30 m^3).

Table 1: Parameters introduced in the software for the development of radon expansion simulations for the three rooms.

Parameter	Specification
Radon concentration emanating from the soil	1000 Bq/m^3
Direction specification method (Radon emanation)	Normal to boundary
Magnitude of air velocity entering the room	0.01 m/s
Temperatureof air velocity entering the room	293.15 K
Material of the walls, ceiling and floor of the rooms	Concrete
Thickness of the walls and ceiling of the rooms	0.1 m

Table 2: Properties of the fluids and the solid used in the simulations.

Property	Radon	Air	Concrete
Density (kgm^{-3})	9.73	1.225	2100
Heat capacity ($Wm^{-1}K^{-1}$)	93.55	1006.43	840
Thermal conductivity ($Wm^{-1}K^{-1}$)	0.0036	0.024	1.4
Viscosity ($kgm^{-1}s^{-1}$)	2.445×10^{-5}	1.789×10^{-5}	–
Molecular weight ($kgkmol^{-1}$)	222	28.966	–

3. Results and Discussion

Figure 2 presents the result obtained in the simulations for each of the three quarters. In a) it can see an image that shows the radon concentration levels for the room that presented a volume of 30 m^3, b) for 100 m^3 and c) for 200 m^3. The images include a histogram with the values of the radioactive activity of the gas (in Bq/m^3) that the program calculated based on the values entered. In each image it can see the *xy* plane (in intense red color) from where radon gas emanates, the *xz* and *yz* planes (in different colors) where radon concentration is reflected as the gas emanates from the ground and interacts with the air and finally a small square surface that represents the level of radon recorded at the exit of the room. It is important to note that the *xz* and *yz* planes are positioned exactly at half the volume of each geometry, in order to show what radon concentration is in the middle of the room. Finally, although the plane that emanates radon is observed in the images, the program does not reflect in the histogram the concentration value of the gas (1000 Bq/m^3), because the software begins to quantify it as the gas interact with the environment. For this reason, the plane has a very intense red color that is not reflected in the histogram.

As can be seen in Figure 2, the three rooms had the highest radon concentration in the lowest part of the room and the lowest concentration was located at the exit of the room. Evidently, this was expected behavior.

In the case of the room that has the lowest volume (30 m^3), the highest radon concentration was 946 Bq/m^3, the lowest was 154 Bq/m^3 and the central part of the room had a concentration that varied between 300 and 700 Bq/m^3. This means that this room is unsafe from the radiological point of view. As will be recalled, the US-EPA recommends mitigating radon gas when its concentration level exceeds 148 Bq/m^3 in a home and 400 Bq/m^3 in workplaces. Therefore, the defined conditions (dimensions of the room, level of concentration of radon emanation, dimensions of the access door and speed of the air that accesses the place) make the space an uninhabitable place. However, since these types of places are generally used as basements or wine cellars, it is not expected that a person will spend much time inside the place.

In the case of the room that presents the volume of 100 m^3, the highest concentration was 351 Bq/m^3, the lowest was 18.26 Bq/m^3 and the central part of the room presented a concentration that varied from 30 to 200 Bq/m^3. It is evident that because the room has larger dimensions the radon concentration values decreased considerably. Although the surface of emanation of the gas also increases, being a larger space the gas interacts with a greater mass of air that comes from the outside, so radon is mitigated more quickly. The room is safer with respect to the previous one, however, if a person had to spend a lot of time inside it, it would still be advisable to increase the air flow inside the space.

Finally, for the room with a volume of 200 m^3, the highest concentration was 55.18 Bq/m^3, the lowest was 5.41 Bq/m^3 and the central part of the room had a concentration below 10 Bq/m^3. The volume of the room allows the air to mitigate radon very quickly, so the room is completely safe.

Therefore, these simulations show that the radon concentration in a closed space decreases as the volume of the room increases. This does not mean that the volume of a space is sufficient to determine the safety of the place, it must always consider the level of concentration of the gas that emanates from the ground and the amount of air entering the place. For this reason, it will always be advisable to properly ventilate any room where a person should stay for a long time.

Conclusion

The concentration of radon within a room may depend on various factors, however, if the level of radon emanating from the ground, its geometry, the characteristics of the interior and the amount of air entering the space remain constant, the dimensions of the room will be a factor that allows to determine if the place could be a safe space from the radiological point of view. In this way, as the volume of the room increases, radon gas is mitigated more quickly and therefore the room has lower concentration levels, although there is a low air flow.

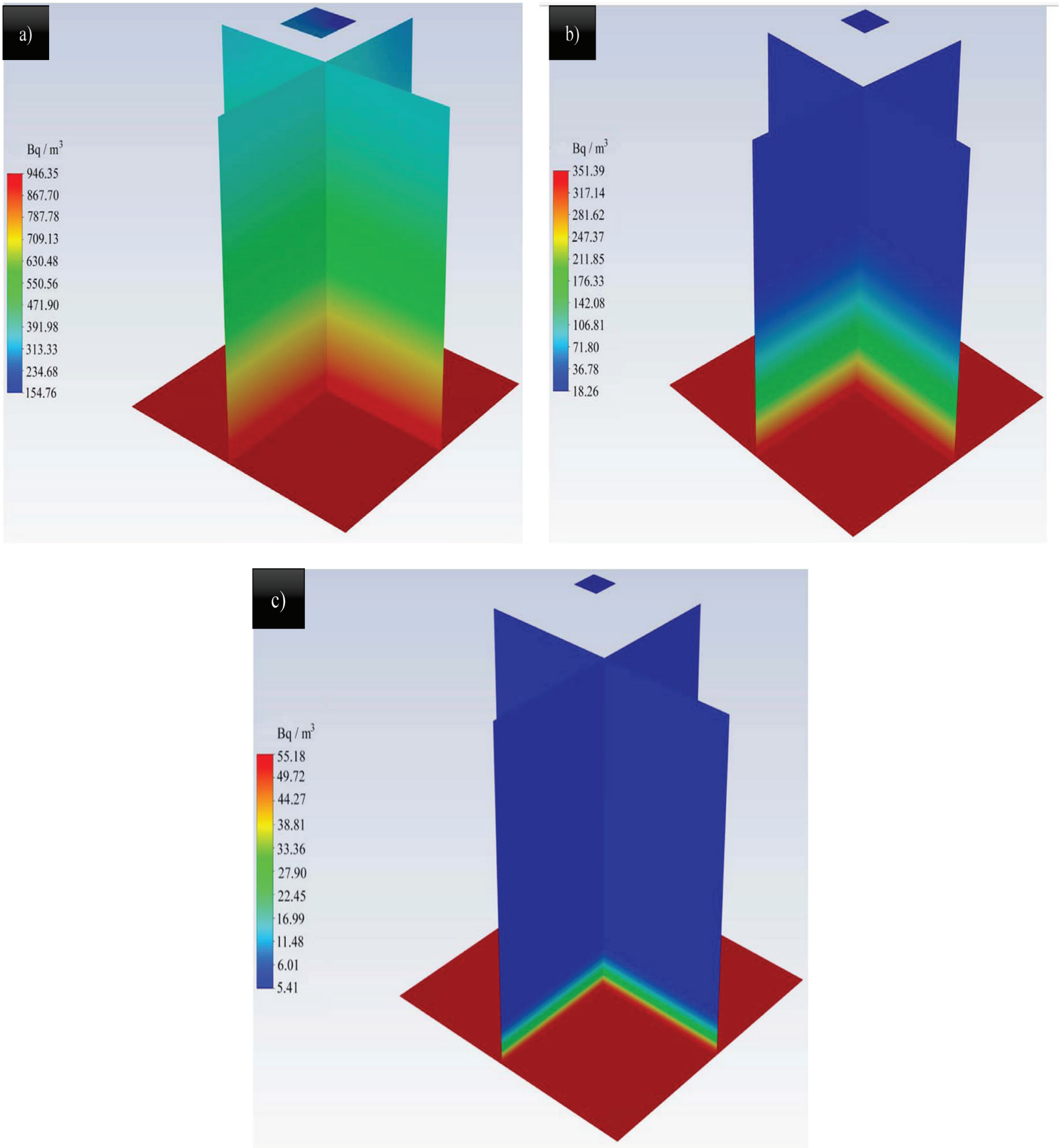

Figure 2: Result of the simulations developed to observe the expansion of radon within rooms with three different dimensions: a) 30 m^3, b) 100 m^3 and c) 200 m^3.

Despite the dimensions of a room, it is always advisable to measure the concentration of radon within any space where a person requires to remain for a long time and maintain a constant air flow when its concentration is greater than the levels recommended by the US-EPA.

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