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DEFINITION AND SENSITIVITY ANALYSIS OF A CFD MODEL FOR THE STUDY OF RADON ENTRY AND ACCUMULATION IN BUILDINGS

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Abstract. *Within the framework of a research project funded by the Spanish Nuclear Safety Council, two different models will be developed to allow the study of radon entry and accumulation in buildings located in different regions of potential risk. The final use will be aimed at the prediction of radon entry rates according with the levels of available information about buildings and environmental parameters. In addition, they should be able to predict the reductions achieved by implementing different types of mitigation solutions. One of them will be developed using the finite element analysis software COMSOL MULTIPHYSICS. This paper presents the first phase of the project, describing the fundamentals of the model and a sensitivity study on some of the parameters it incorporates: radon levels in the ground and soil permeability; envelope conditions in terms of porosities, permeabilities, diffusion coefficients, discontinuities; environmental parameters such as pressure conditions, indoor and outdoor temperature, winds, moisture content of the ground. The results and the analysis of their feasibility of application will be compared later with the second model developed with the STELLA software. In a second phase, both models will be compared and calibrated using the monitored data from two real buildings located in areas with high radon exhalation potential.*

Keywords: *radon, mitigation, radon predictive model, CFD, radon immission*

1. INTRODUCTION

Radon (^{222}Rn) is a radioactive gas, produced by the decay of radium isotopes (^{226}Rn). These isotopes occur naturally in soil, rocks, water and building materials [1]. Through transport mechanisms, mainly advection and diffusion, radon penetrates the building envelope.

With a half-life of 3.6 days, radon accumulates in indoor spaces. Radon progeny can be inhaled and deposited in lung tissue. The particles generated during the decay can damage lung cells, increasing cancer risk. Radon is considered by the World Health Organization as one of the main causes of lung cancer [2].

In locations with high radon content, indoor mitigation processes are based on preventing the penetration of the gas. To this end, it is essential to understand the transport and entry mechanisms, that cause radon generated within the soil to move through the soil and penetrate the building envelope [3]. These mechanisms are influenced both by the properties of the soil [4] and the building envelope, as well as by temporary actions, such as weather or building use [5][6]. Better control of transport and entry phenomena allows for more efficient design of mitigation systems.

The study of each phenomenon involved has been developed in recent years through semi-empirical equations [7][8][9][10]. On the one hand, the equations help to estimate gas generation and transport processes from measurable data. On the other hand, the equations help to integrate different parameters, such as porosity, permeability, and soil moisture, simplifying their study [11].

The integration of parameters and equations can be done through mathematical modeling [12][8]. The use of finite element analysis software, such as COMSOL Multiphysics, facilitates the work of integrating equations and parameters and generates detailed studies [13][14]. The information obtained can be applied directly to the problem to be treated or used to develop simplified models that adapt to the data available for each building. This last point is one of the objectives of the RADNUM-CSN-01 project, funded by the Spanish Nuclear Safety Council (CSN), to which this work belongs.

This paper presents the progress in the development of a Computational Fluid Dynamics (CFD) model for the study of radon gas movements. The model calibration is based on data obtained from a real building constructed in 2006 for the study of radon gas [15]. Since its construction, the building has been monitored on several occasions as part of radon gas studies.

The CFD model is based on the data available from the real model. On the other hand, an analysis of the sensitivity to different parameters is performed. This will allow adapting the model to different scenarios, as well as facilitating simplifications to future models.

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2. Methods and materials

2.1. The real model

The CFD model is based in the data recorded in a real building placed in Saelices el Chico (Salamanca, Spain). It is located near a uranium mine.

The prototype building (Figure 1) was specifically designed for the study of radon entries and mitigation techniques. The building consists of two floors, the lower floor being a semi-basement. Both floors are connected by a staircase, which forms a single space with the semi-basement. The upper room is separated by a partition wall.

Figure 1. Prototype building in Saelices el Chico (Salamanca, Spain).

The building is constructed using standard Spanish construction techniques. The foundation is made of footings and concrete slab separated from the ground by a layer of gravel. The enclosure is built in brick and has openings (windows and door) on opposite facades.

The various parameters of the building have been monitored since 2006.

2.2. The CFD model

The simulation model is developed in COMSOL Multiphysics 6.0.0.318. The COMSOL modules applied are the Darcy's Law, Transport of diluted species in porous media, and Transport of diluted species in fractures. Preliminary studies are carried out to determine the extent of the terrain simulation. The model with medium meshing can be seen in Figure 2.

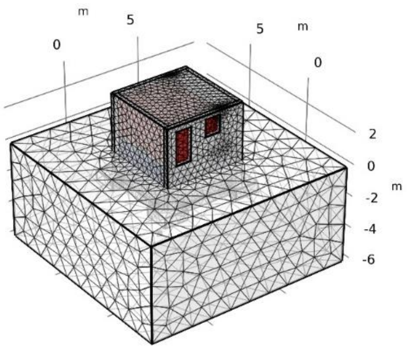

Figure 2. CFD model. Blue: Semi-basement. Red: First floor. Green: Gravel plan under the slab.

The simulations are performed on a static 3-D model. Time-dependent parameters are expected to be incorporated in the future.

2.3. Working data and default parameters

The working data are based on the data extracted from the real model. The simulations were developed using parametric studies, with the variation of one parameter at a time. Table 1 shows some of the main default parameters used. The ^{226}Ra Activity in soil has been estimated by gamma spectrometry based on soil samples (average value 1306±70 Bq/kg). The soil permeability has been estimated as the average soil permeability. The parameters that are not measured in the actual model are estimated by their typical value. A more complete review of the data collected on site can be found at [16].

Table 1. Main default parameters used.

Parameter	Symbol	Value	Units
^{226}Ra Activity	A_{ra}	1306	Bq/kg
Radon decay constant	λ	$7.55x10^{-3}$	h^{-1}
Diffusion coefficient of radon in air	D_0	$1.1x10^{-5}$	m^2/s
Soil permeability	k_{soil}	$1x10^{-12}$	m^2
Soil porosity	E_{soil}	0.5	
Emanation coefficient	f	0.29	
Water saturation fraction	m	0.35	

In these first approximations, the target value for the calibrated model will be taken as the range of 50,000 Bq/m^3 in the semi-basement. This value corresponds to the data recorded in the first years of study of the demonstrator building.

However, a simplified model is used for the individual analysis of each of the parameters. This model eliminates cracks, weather conditions, envelope permeability and other factors. Although the range of values obtained is significantly lower than the target value, this analysis provides information on the individual trends of each parameter. This information will be useful in the development of the final model.

New measurements are currently being made on the real model, incorporating the monitoring of new parameters that were not recorded in the first studies. These parameters include continuous measurements of radon concentration, temperature, and pressure in soil, and differential pressures between the ground and the different spaces in the building. The data obtained will be used to update the CFD model and correct faults.

3. Results and discussion

Parametric studies can be grouped into soil, construction, climatological and usage parameters. For each of the parameters, the characteristics with the greatest potential for variability are studied. The model also allows variations of two or more parameters simultaneously. This paper presents some of the most relevant results obtained in the simulations.

3.1. Soil parameters

Soil parameters include radon generation and transport from the soil to the building envelope. The parametric analysis includes radium content of the soil, radon generation, radon decay, and soil properties such as porosity, permeability, moisture, and diffusion coefficient.

Figure 3 shows the increase in indoor radon levels depending on the water content of the soil. As the water content increases, the radon inside the building increases. However, from 45-50% humidity, the pores become saturated with water, reducing radon entry.

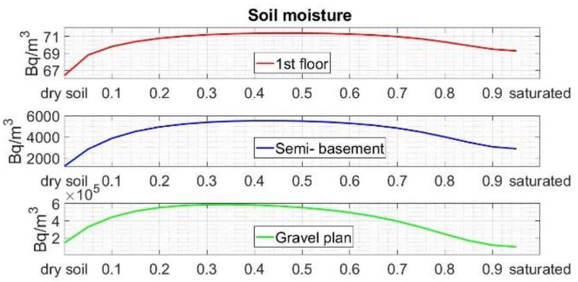

Figure 3. Parametric study of soil moisture.

The diffusion coefficient is a parameter that depends on both the porosity of the dry soil and its water content [12]. The graph in Figure 4 shows the variation of the diffusion coefficient according to the degree of soil moisture, and its influence on indoor radon concentrations. As with soil moisture, radon concentration increases until the diffusion coefficient is in the range of 10^{-6} m^2/s, and then begins to decrease. The pore water content of the soil is dominant over the porosity.

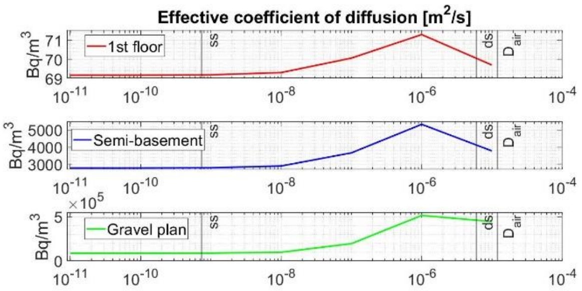

Figure 4. Parametric study of effective diffusion coefficient. ss: Saturated soil. ds: Dry soil.

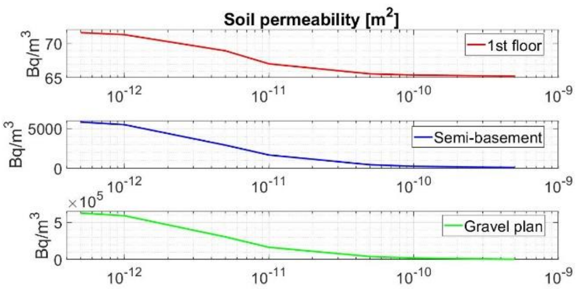

Figure 5. Parametric study of soil permeability.

By varying the permeability of the soil, the model can be adapted to different types of terrain (Figure 5). The higher permeability facilitates gas movement, increasing exhalation and air exchange. In this case, radon ingress is reduced as the permeability of the soil becomes similar to that of the gravel layer under the slab. Other parameters being equal, the difference in radon input may be due to finding the easiest path for the gas to exit.

3.2. Building and construction parameters

In the construction parameters of the building, it is possible to study both the influence of the different constructive materials and techniques, and the presence of cracks or faults in the construction. In addition, the CFD model allows incorporating both the physical characteristics of the building materials and their radon content and generation. Figure 6 shows the modeling of the foundation and a perimeter fracture in the slab.

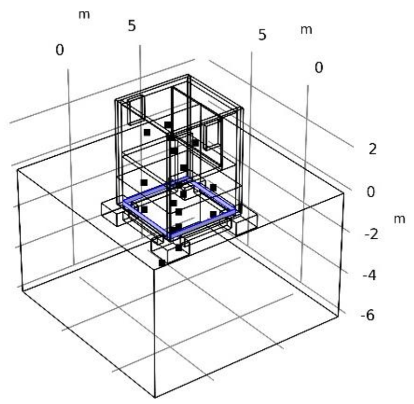

Figure 6. Model with foundation footings and slab with perimeter fracture.

Figure 7 shows the influence of the perimeter fracture width on the slab. In this case, the fracture is not clean, but a permeability of $9x10^{-9}$ m^2 is assumed. Radon inputs increase as the fracture width increases. However, the trend is asymptotic, so that once direct contact is established between the gaps, the size of the contact becomes less relevant.

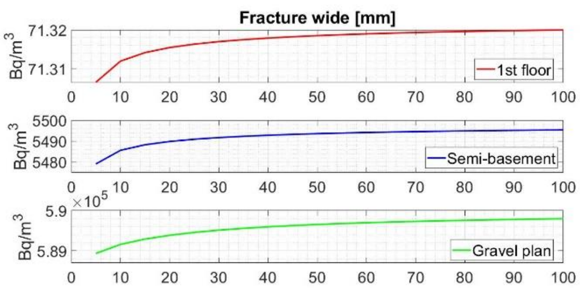

Figure 7. Parametric study of fracture wide. Fracture permeability: $9x10^{-9}$ m^2 (equivalent to gravel permeability). No-clean fracture hypothesis.

The fracture study also includes fracture permeability as well as fracture depth.

3.3. Use and weather parameters

The use parameters include those associated with human activity inside the building. They include the opening of doors and windows, and the establishment of different types of ventilation.

On the other hand, climatological parameters incorporate the influences of the external environment. They are also affected by the constructive characteristics of the building, such as the airtightness of the envelope or the tightness of the windows. The influence of some parameters, such as pressure and temperature, depends on the conditions existing in the interior space. The influence of pressure on radon gas inputs is usually estimated by considering the differential pressure between indoors and outdoors (Figure 8). In the stationary model, the soil pressure is considered to equalize with the external pressure. If the pressure difference between indoors and outdoors is reduced by about 10 Pa, the indoor radon concentration increases by 4%.

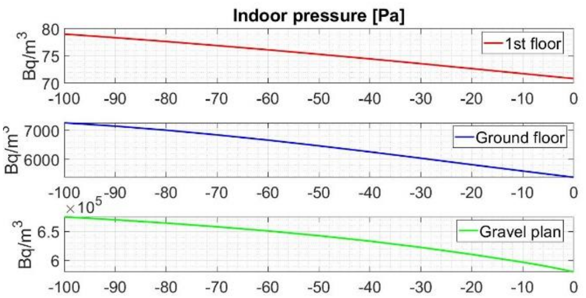

Figure 8. Parametric study of indoor pressure.

In addition to the analysis of concentrations, the movement of gases can be further investigated by simulating radon inflows. Figure 9 shows the wind modeling, using positive and negative pressures (10 Pa) on opposite facades.

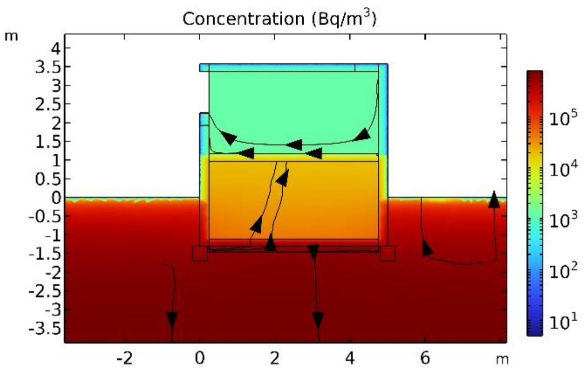

Figure 9. Parametric study of fracture wide.

Weather parameters can be modeled in time-dependent studies. In studies on real models, daily radon cycles have been detected. The simulation study could help to determine the parameters that affect them, as well as their influence on radon concentrations.

5. Conclusion

CFD models allow the detailed study of radon gas movements. These models facilitate the simulation of complex building structures. They also allow the simultaneous handling of several parameters for the elaboration of the simulations. During the creation of a model, it is possible to assign properties to each of the materials that compose it (soil, building materials, structural materials...), as well as to define temporal parameters, such as weather or indoor pressure. This results in very accurate models and simulations.

However, the use of these models is limited by the information available on the building to be analyzed. A very accurate simulation requires the prior monitoring of many parameters over time. However, in most of the buildings to be mitigated, the knowledge of these data is very limited. The determination of the influence of each of the parameters on the transport and inflow of gas to the buildings allows estimates to be made in the absence of some data. These estimates can provide reference ranges to assist in the design of mitigation systems.

On the other hand, having an accurate simulation model helps to develop simplified models, which facilitate estimates of radon inputs with low data and time requirements.

The work developed in this article presents the advances made on a CFD model, which will later be used to calibrate and develop other applications for radon mitigation.

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