Journal of Environmental Radioactivity 177 (2017) 280–289

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

A finite element model development for simulation of the impact of slab thickness, joints, and membranes on indoor radon concentration

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ARTICLE INFO

Article history:
Received 6 March 2017
Received in revised form
30 May 2017
Accepted 5 July 2017

Keywords:
Radon
Exhalation
Generation
Diffusion
Advection
Buildings materials
Slab joints

ABSTRACT

The focus of this study is broadly to define the physics involved in radon generation and transport through the soil and other materials using different parameter-estimation tools from the literature. The effect of moisture in the soil and radon transport via water in the pore space was accounted for with the application of a porosity correction coefficient. A 2D finite element model is created, which reproduces the diffusion and advection mechanisms resulting from specified boundary conditions. A comparison between the model and several analytical and numerical solutions obtained from the literature and field studies validates the model.

Finally, the results demonstrate that the model can predict radon entry through different building boundary conditions, such as concrete slabs with or without joints, variable slab thicknesses and diffusion coefficients, and the use of several radon barrier membranes. Cracks in the concrete or the radon barrier membrane have been studied to understand how indoor concentration is affected by these issues.

1. Introduction

Radon (^{222}Rn) is a noble gas and is a decay product of radium (^{226}Ra). Both radionuclides belong to the uranium decay chain (^{238}U). Being a noble gas with a relatively long half-life (3.8 days), radon can move through interconnected pores in the soil, reach the Earth's surface, and penetrate into building interiors. Poor ventilation conditions or cracks in the construction systems favour the accumulation of radon inside dwellings, thus leading to health risks due to the inhalation of radon decay products.

The study of radon generation and transport through a porous medium and its influence on surface radon exhalation is important for both, prevention and best building practices, due to action measures against this gas (Cosma et al., 2015).

Our study examines radon generation and transport mechanisms from soil to air and compares with simplifications or assumptions made by other authors. The discussion focuses on the use and omission of variable factors that affect the value of surface radon flux density at the atmospheric level. Finite element software was used to perform the model calculations. In addition, the model was validated by comparing the results to existing literature and to actual field measurements. Finally, the finite element model is applied to six specific examples that show different types of slab on grade and building pathologies.

2. Correlation of radon generation and migration parameters

The transport of radon gas (^{222}Rn) through a porous medium occurs due to two mechanisms: diffusive flux and advective flux.

Diffusive flux is governed by Fick's Law and relates the diffusion coefficient to the concentration gradient. Diffusive flux density can vary depending on the diffusion coefficient that is used (Nazaroff et al., 1988).

Definitions for the diffusion coefficient proposed by several authors are described below:

The bulk diffusion coefficient D establishes a relationship between the gas concentration gradient in the internal air of a porous medium and the flux density through a geometric area.

$$\vec{Jd} = -D\nabla C \quad (1)$$

where

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http://dx.doi.org/10.1016/j.jenvrad.2017.07.006
0265-931X/

$\overrightarrow{Jd}$: Radon gas diffusive flux density per geometric unit area [Bq m^{-2} s^{-1}]
D: Radon gas bulk diffusion coefficient [m^2 s^{-1}]
C: Radon gas concentration in the internal air of a porous medium [Bq/m^3]

The use of an effective diffusion coefficient D_e establishes a relationship between the gas concentration gradient in the internal air of a porous medium and the flux density through the pore area.

$$\overrightarrow{Jd_p} = -D_e \nabla C \tag{2}$$

where

$\overrightarrow{Jd_p}$: Radon gas diffusive flux density per unit of pore area in the medium [Bq m^{-2} s^{-1}].
D_e: Radon gas effective diffusion coefficient [m^2 s^{-1}].

Both coefficients can be related based on the medium porosity in the absence of moisture (L. Font, 2008) as follows:

$$D = \varepsilon D_e \tag{3}$$

The ground moisture saturation ratio relates both coefficients through the partition corrected porosity (Andersen et al., 1999).

$$D = \beta D_e \tag{4}$$

where $\beta = (1 - m + Lm)\varepsilon$, which is related to total porosity (ε), the fraction of moisture saturation (m), and the radon solubility coefficient in water (L). The effective diffusion coefficient (D_e) may be estimated based on the moisture content within the medium (Rogers and Nielson, 1991).

$$D_e = \varepsilon D_a \exp\left(-6m\varepsilon - 6m^{14\varepsilon}\right) \tag{5}$$

where $D_a = 1.1 \times 10^{-5} m^2/s$, which is the value for the radon diffusion coefficient in external air. This coefficient can be estimated by correlation with the medium temperature (T) in degrees Kelvin (Schery and Wasiolek, 1998)

$$D_a = 1.1 \times 10^{-5} (T/273)^{3/2} \tag{6}$$

and m, the fraction of moisture saturation (Sun et al., 2004).

$$m = \frac{(w\rho_0)}{(\rho_w \varepsilon)} \tag{7}$$

where

ρ_0: Bulk dry density [kg m^{-3}]
ρ_w: Water density [kg m^{-3}]
w: Water mass content [-]

Fig. 1 shows how the moisture content can neutralise diffusive movement through the porous medium due to a decrease in the effective diffusion coefficient as the fraction of moisture saturation increases.

The advective flux density of gas across a porous medium is described by Darcy's Law, which relates the pressure gradient to the apparent speed of a fluid moving through a porous medium.

$$\vec{v} = -\left(\frac{k}{\mu}\right) \nabla P \tag{8}$$

where

$\vec{v}$: Darcy's superficial velocity vector, defined as the flux per geometric unit area [m s^{-1}]
k: Medium-gas permeability [m^2]
μ: Dynamic viscosity of the gaseous phase in a porous medium [Pa s]
∇P: Pressures gradient [Pa]

Soil-gas permeability can be estimated based on the moisture, porosity and average arithmetic size of the ground particles (da) (Rogers and Nielson, 1991) as follows:

$$k = \left(\varepsilon/110\right)^2 da^{4/3} \exp\left(-12m^4\right) \tag{9}$$

This parameter is essential when determining the behaviour of surface exhalation. Flux density remains relatively constant with a slight increase for $k < 10^{-12}$ m^2 permeability values, whereas it increases rapidly for $k > 10^{-12}$ m^2 values, as shown in Fig. 2.

Under natural conditions and in the absence of artificial pressurisation, Darcy's Law can be used with the assumption that air has constant density, that flux is laminar, and that pressure distribution is governed by the Laplace equation (Jiranek and Svoboda, 2007).

Based on Darcy's velocity, advective flux density is defined across the pore area as follows:

$$\overrightarrow{Ja_p} = \left(\frac{C}{\varepsilon}\right) \vec{v} = -\left(\frac{C}{\varepsilon}\right) \left[\left(\frac{k}{\mu}\right) \nabla P\right] \tag{10}$$

Therefore, to determine the advective flux density across a geometric or bulk area, it is necessary to multiply Eq. (10) by porosity (Holford et al., 1993).

$$\overrightarrow{Ja} = C\vec{v} = -C\left[\left(\frac{k}{\mu}\right) \nabla P\right] \tag{11}$$

Finally, the total radon flux density can be calculated using a combination of the diffusive and the advective mechanisms as follows:

$$\overrightarrow{J_T} = \overrightarrow{Jd} + \overrightarrow{Ja} = -D \nabla C + C\vec{v} = -\beta D_e \nabla C - C\left(\frac{k}{\mu}\right) \nabla P \tag{12}$$

Below is a definition of the differential equation that generally governs radon transport in a porous medium considering the diffusion-advection mechanisms and the change in the number of gas atoms due to generation and decay (Clements and Wilkening, 1974).

$$\frac{\partial \varepsilon C}{\partial t} = D \nabla^2 C + \left(\frac{k}{\mu}\right) \nabla C \nabla P - \lambda \varepsilon C + \varepsilon G \tag{13}$$

where

λ: Radon decay constant [s^{-1}]
t: Time [s]
G: ^{222}Rn generation (in terms of activity concentration) in a porous medium per unit volume and time [Bq m^{-3} s^{-1}]

This equation is valid for a homogeneous, isothermal medium.

The first term after the equality sign represents diffusion