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Evaluation of indoor radon equilibrium factor using CFD modeling and resulting annual effective dose

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ABSTRACT

The equilibrium factor is an important parameter for reasonably estimating the population dose from radon. However, the equilibrium factor value depended mainly on the ventilation rate and the meteorological factors. Therefore, this study focuses on investigating numerically the influence of the ventilation rate, temperature and humidity on equilibrium factor between radon and its progeny. The numerical results showed that ventilation rate, temperature and humidity have significant impacts on indoor equilibrium factor. The variations of equilibrium factor with the ventilation, temperature and relative humidity are discussed. Moreover, the committed equivalent doses due to ^{218}Po and ^{214}Po radon short-lived progeny were evaluated in different tissues of the respiratory tract of the members of the public from the inhalation of indoor air. The annual effective dose due to radon short lived progeny from the inhalation of indoor air by the members of the public was investigated.

1. Introduction

Radon and its progeny are present in the indoor environment since its parent nuclei radium are present in building materials and the soil. It is well known that the inhalation of radon and its decay products contributes a major part (more than 50%) of the natural background radiation dose to the humans (United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR, 2000). Further, in the indoor environment, the inhalation doses due to the ^{222}Rn are predominantly contributed from its decay product concentrations. But, the direct measurements of the concentrations of all short-lived decay products of radon are difficult and limited. However, the effective dose assessment is usually carried out by measuring radon concentration and applying an equilibrium factor. Therefore, the most accurate estimation of this equilibrium factor is the guarantee of an accurate dose assessment (Forkapic et al., 2013; Abuelhia, 2017; Chen, 2005; Kojima, 1996; United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR, 2000).

According to the ICRP recommendations, the indoor equilibrium factor was estimated a value 0.4. However, previous experimental studies have shown that the meteorological factors such as the ventilation rate, temperature and moisture have impacts on indoor equilibrium factor (Rozas et al., 2016; Chen et al., 1998; Li et al., 2011; Ramola et al., 2003; Chu and Liu, 1996).

In recent time, Computational Fluid Dynamics (CFD) has taken outstanding position for simulation of indoor radon problems (Chauhan et al., 2014; Agarwal et al., 2014). CFD solves the governing fluid equations and provides spatial and temporal field solution of variables such as pressure, temperature, energy density. It also provides velocity flow field and the dispersion pattern of indoor pollutant. There exist studies wherein CFD has been used to study the radon dispersion in dwellings (Urosevic and Nikezic, 2008; Akbari et al., 2013; Lee et al., 2016; Rabi and Oufni, 2017a,b). However, these studies do not explain how physical and environmental factors affect the indoor equilibrium factor. This work attempts to employ CFD to study the effect of meteorological factors such as the ventilation rate, temperature and moisture on equilibrium factor in a house. We also determined annual committed equivalent doses in the tissues of the respiratory tract due to the inhalation of radon short-lived daughters by the members of the public.

2. The numerical method

2.1. Physical model

The studied model house plan is illustrated in Fig. 1. It occupies a surface of 100 m^2 (10 m long by 10 m wide and 3 m high). It consists of a living room of 28 m^2 in surface, two bedrooms each one has 20 m^2 in surface, a kitchen of 12 m^2 in surface, bathroom and restroom each one has surface 2 m^2. The house is oriented west-east, the walls west and east are facing outdoors, and each of the outer walls has two windows, while the other two sides (north and south) have no windows. Thus, the

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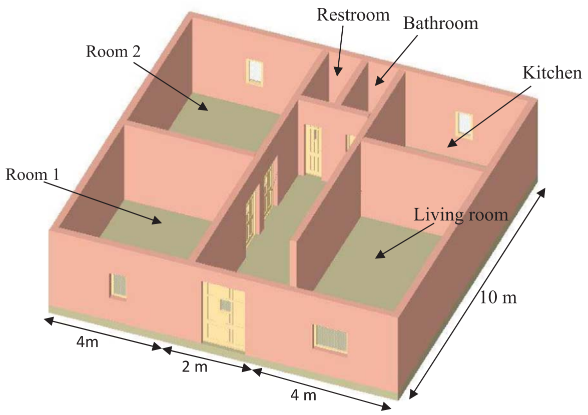

Fig. 1. The geometry of the house plan.

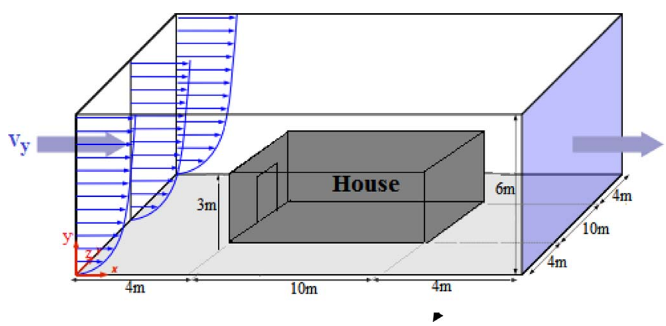

Fig. 2. Dimensions of the computational domain.

Table 1
Data obtained for the radium activities (^{226}Ra) and radon exhalation rate of different studied building material samples (Rabi and Oufni, 2017b).

Sample	$D_T^{CR} \times 10^3$ (trcm^{-2}s^{-1})	$D_T^{LR} \times 10^3$ (trcm^{-2}s^{-1})	$A_c(^{226}Ra)$ (Bqkg^{-1})	E (mBqm^{-2}h^{-1})
Plaster (ceiling)	1.06 ± 0.21	0.32 ± 0.05	1.37 ± 0.21	139.67 ± 21.79
Concrete (walls)	1.98 ± 0.20	0.61 ± 0.06	2.55 ± 0.26	259.86 ± 26.61
Marble (floor)	1.37 ± 0.21	0.42 ± 0.06	1.77 ± 0.27	180.20 ± 27.91

ventilation in the house is provided by two windows in west wall, that is open, and the air exits are across two windows of east wall.

2.2. The numerical approach

Computational fluid dynamics is based on the resolution of the governing equations which describe the flow field in the computational domain, namely the continuity equation for mass transfer, the Navier–Stokes equation for momentum transfer and the thermal energy equation for heat transfer.

For a steady incompressible flow and Newtonian, time-averaged continuity, Navier–Stokes and energy equations can be, respectively, written as:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[(\mu_t + \mu)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g \tag{2}$$

$$\frac{\partial(u_i T)}{\partial x_i} = \alpha\left(\frac{\partial^2 T}{\partial {x_i}^2}\right) \tag{3}$$

where x is the coordinate axis in the direction i (i = 0, 1, 2), u_i corresponds to the mean velocity in i direction (m s^{-1}), ρ is the air density (kg m^{-3}), P is pressure (N m^{-2}), μ_t is the turbulent viscosity (N s m^{-2}), μ is the molecular viscosity (N s m^{-2}), g is the gravitational acceleration (m^2 s^{-1}), T is temperature and α is thermal diffusivity (m^2 s^{-1}). According to the widely used two-equation k – ε model, μ_t can be expressed as follows:

$$\mu_t = C_\mu \rho k^2/\varepsilon \tag{4}$$

where C_μ is a constant and k and ε are the turbulent kinetic energy (m^2 s^{-2}) and its dissipation rate (m^2 s^{-3}), respectively. In order to close the model two other equations are required, namely the transport equations for k and ε:

$$\frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \mu_t\frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\mu_t\frac{\varepsilon}{k}\frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{6}$$

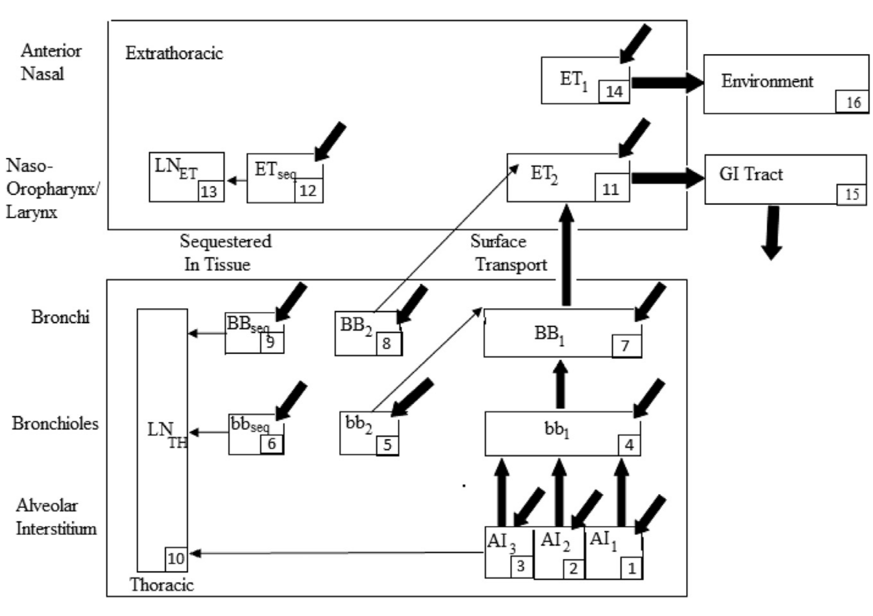

Fig. 3. Compartment model showing particle transport from each region.