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Numerical modeling of the sources and behaviors of ^{222}Rn, ^{220}Rn and their progenies in the indoor environment—A review

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ABSTRACT

^{222}Rn, ^{220}Rn and their short-lived progenies are well known radioactive indoor pollutants, identified as the leading environmental cause of lung cancer next to smoking. Apart from the conventional measurement methods, numerical modeling methods are developed to simulate their physical and decay processes in ^{222}Rn and ^{220}Rn's life cycle, estimate their levels, concentration distributions, as well as effects of control strategies in the indoor environment. In this article, we summarized the numerical models used to illustrate the physical processes of each source of ^{222}Rn and ^{220}Rn entry into the indoor environment, and the application of Jacobi room models and CFD (Computational Fluid Dynamic) models used to present the behaviors of indoor ^{222}Rn, ^{220}Rn and their progenies. Furthermore, we consider that the development of numerical modeling of ^{222}Rn and ^{220}Rn would have a bright prospect in the directions of stochastic methods based on a steady-state model, the fine simulation of the time-dependent model as well as the multi-dimension model.

1. Introduction

Radon is a naturally occurring radioactive gas generated by the decay of uranium and thorium in rocks and soils. Among the isotopes of radon, ^{222}Rn ($T_{1/2}$ = 3.8235 d) is a member of the uranium (^{238}U) natural decay series (Fig. 1), and ^{220}Rn ($T_{1/2}$ = 55.6 s) is a member of the thorium (^{232}Th) natural decay series (Fig. 2). Presently, ^{222}Rn and ^{220}Rn are commonly known as radon and thoron, respectively. Uranium, radium, and thorium occur naturally in rocks and soils, and provide a continuous source of radon. Radon can escape from the earth's crust either by molecular diffusion or by convection, and as a consequence, radon is present in the air of both the outdoor and indoor environment (ICRU, 2012). Radon gas is known as the most critical natural source of ionizing radiation with approximately 40% of the annual effective dose from all sources of radiation (Pacheco-Torgal, 2012). In addition, radon has become recognized as one of the most important indoor air pollutants. According to the World Health Organization (WHO), radon, following smoking, constitutes the second leading cause of lung cancer in the general population (WHO, 2009). Numerous studies have found that indoor radon is generally affected by following factors: 1) building materials (Awhida et al., 2016; Csige et al., 2013; Janik et al., 2015); 2) soil radon exhalation (Gusain et al., 2009; Nazaroff, 1992); 3) indoor and outdoor air exchange (Andersen, 2001); and 4) water from wells (Vogiannis and Nikolopoulos, 2014). In the past, it has been assumed that the contribution from ^{220}Rn and its progenies to the total exposure of radon isotopes was limited to around 10% (UNSCEAR, 2006). However, some experimental studies (Bochicchio et al., 1996; Doi et al., 1994; Ma et al., 1997) have demonstrated that exposure to ^{220}Rn may well exceed those of other radon isotopes. Contrary to ^{222}Rn, because of its short half-life of 55.6 s, the concentration distribution of ^{220}Rn in the indoor environment is heterogeneous, resulting in low and even undetectable levels of ^{220}Rn away from the wall of the building indoors. The exposure of ^{220}Rn varies greatly and also depends on the used building materials. Therefore, the ^{220}Rn exposure cannot be ignored as in the past.

Conventionally, passive method using dosimeters and active method using electronic devices were used to measure the ^{222}Rn and ^{220}Rn activity concentrations. In addition, some numerical modeling methods were also developed to estimate the levels and concentration distributions of indoor ^{222}Rn and ^{220}Rn (Jelle, 2012; Stoulos et al., 2003), and simulate the processes of radon entry into houses (Andersen, 2001), to evaluate the effects of control strategies of ^{222}Rn, ^{220}Rn and their progenies in indoor environments.

In terms of numerical models estimating the indoor ^{222}Rn and ^{220}Rn concentrations, generally, most researchers established them based on the conservation equation of mass (Park et al., 2016),

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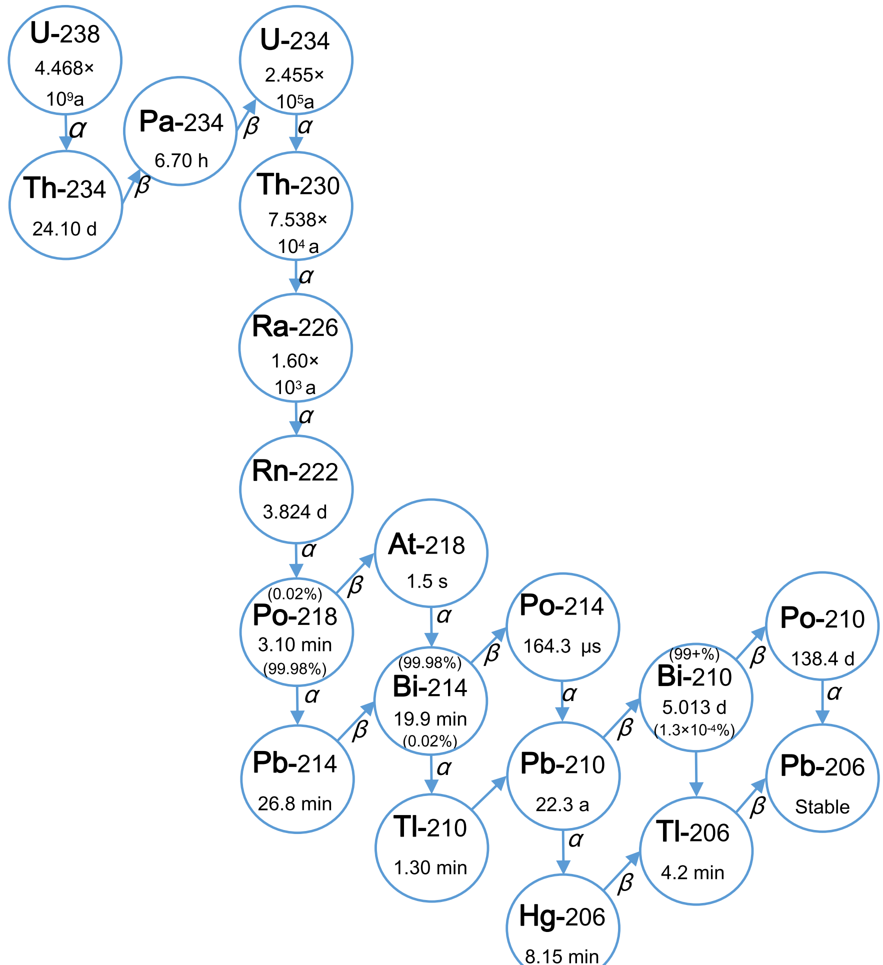

Fig. 1. Decay chain of uranium-238 series.

$$\text{Indoor accumulation} = \text{Entry} + \text{Exchange} - \text{Decay reaction} \quad (1)$$

According to equation (1), the ^{222}Rn and ^{220}Rn concentrations are affected by their sources and sinks. The sources of ^{222}Rn and ^{220}Rn entry into the indoor environment include the process of the exhalation from the soils, building materials, and water into the indoor environment by natural and mechanical ventilation and infiltration. The sinks of ^{222}Rn and ^{220}Rn, decreasing their indoor concentrations, include the processes of decays, and gas release or reduction by the use of indoor filtration equipment and the natural and mechanical ventilation.

In this article, we summarized the numerical models used to illustrate the physical processes of each source of ^{222}Rn and ^{220}Rn entry into the indoor environment, and the application of Jacobi room models and CFD (Computational Fluid Dynamic) models used to present their indoor behaviors. Furthermore, we also present a prospect of the development of numerical modeling of ^{222}Rn and ^{220}Rn in the directions of stochastic methods based on the steady-state model, the fine simulation of time-dependent model as well as the multi-dimension model.

2. Numerical models of the sources of indoor ^{222}Rn and ^{220}Rn

Indoor ^{222}Rn and ^{220}Rn concentration may be affected by many factors, mainly including long-term climate change, seasonal climate change, ground cover and vegetation, soil porosity and grain size, as well as the type of construction materials, air-tightness, ventilation rate, type of ventilation, and construction age of the building (Suzuki et al., 2010; Vogiannis and Nikolopoulos, 2014). The primary sources of indoor ^{222}Rn and ^{220}Rn include gas from the soil adjacent to house, earth-based building materials, domestic water, outdoor air, and natural gas, as shown in Fig. 3. The soil and building materials are considered to be mainly responsible for the indoor ^{222}Rn concentration. Compared to ^{222}Rn, because of the short half-life of 55.6 s, the indoor ^{220}Rn originates mainly from building materials. The concentration of ^{220}Rn changes with the distance from the wall, because ^{220}Rn needs time to travel, and it decays on the way. Therefore, the concentration of ^{220}Rn is higher near the wall (Doi et al., 1994). Other sources generally contribute only a minor fraction of total indoor activity concentration.

2.1. Entry into houses from soil gas

Soil gas, as the primary source of indoor radon, has 4 potential entrance processes: 1) generation of radon in the soil; 2) transport of radon through soil; 3) transport through the building shell (e.g. through cracks in the slab); and 4) driving forces such as difference of pressure between indoor and outdoor. Some scientists had used modeling methods to investigate these processes (Bonnefous et al., 1992; Gadgil, 1992; Robinson and Sextro, 1997).

Scott (1985) reported a numerical investigation of the effects of wind speed and direction (the wind-induced ground-surface pressure) on radon entry rates using a finite-element model of a simple building. Nazaroff et al. (1985) used a model to analyze the radon transport into house, and found that pressure-driven flow was an important parameter for radon entry into house; on the contrary, the air-exchange rate had only a small effect on indoor radon concentration. Loureiro et al. (1990) developed a 3-dimensional finite-difference model to simulate the production and decay of ^{222}Rn in the soil, the diffusive and convective