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Modeling and experimental examination of water level effects on radon exhalation from fragmented uranium ore

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ABSTRACT

In this study, a one-dimensional steady-state mathematical model of radon transport in fragmented uranium ore was established according to Fick's law and radon transfer theory in an air-water interface. The model was utilized to obtain an analytical solution for radon concentration in the air-water, two-phase system under steady state conditions, as well as a corresponding radon exhalation rate calculation formula. We also designed a one-dimensional experimental apparatus for simulating radon diffusion migration in the uranium ore with various water levels to verify the mathematical model. The predicted results were in close agreement with the measured results, suggesting that the proposed model can be readily used to determine radon concentrations and exhalation rates in fragmented uranium ore with varying water levels.

1. Introduction

Radon is a radioactive gas that is colorless, odorless, tasteless, chemically inert, and 7.5 times heavier than air. It is a powerful natural alpha-emitter with a 3.8-day half-life. Many studies have shown that individuals who inhale radon and its progeny with high concentration for sustained durations are more susceptible to lung cancer (Field et al., 2000; Darby et al., 2005; Al-Zoughool and Krewski, 2009).

Radon pollution in a uranium mine atmosphere can originate from a variety of sources. Among the manmade sources, uranium tailings and uranium ore from heap leaching are particularly notable; they contain almost ^{226}Ra and have activity concentration basically identical to ^{238}U in the ore prior to extraction (Gulson et al., 2005; Sahoo et al., 2010). Due to the impact of the production process and natural environmental factors such as rainfall, large amounts of water are accumulated in heap leaching uranium ore and uranium tailings. These stacked bodies are composited by particle uranium ore with similar particle size. In addition, some or all of the stacked bodies are immersed in static water.

At present, domestic and foreign scholars typically focus on radon migration in porous uranium ore such as construction materials and uranium tailings (Petropoulos et al., 2001; Righi and Bruzzi, 2006; Sahoo et al., 2010; Kumar et al., 2014; Fan et al., 2015; Sundar et al., 2015). There have been fewer studies on the precipitation of surface radon exhalation on uranium ore with bulk-type characteristics or those which are covered by water.

Adler analyzed the influence of water saturation on radon exhalation by establishing a precise description of a porous uranium ore at the pore scale and determining phase configurations based on the first principles of fluid mechanics (Adler and Perrier, 2009). Radon exhalation is a part of the process of ^{222}Rn release from the connected uranium ore pore space – radon exhalation rate increases as water content decreases because the recoil range of radon in water is smaller than that in air (Barillon et al., 2005; Adler and Perrier, 2009). Chanyotha designed an automated sediment equilibration laboratory system to evaluate radon flux and water radon concentration in pores (Chanyotha et al., 2014). Numerous studies across the globe pertaining to radon exhalation have been focused on the surface of uranium tailings and construction materials that maintain certain levels of humidity (Ferry et al., 2001; Sahoo et al., 2010). To date, however, there has been no definitive study on the effects of water level changes in the uranium ore to its surface radon exhalation rate.

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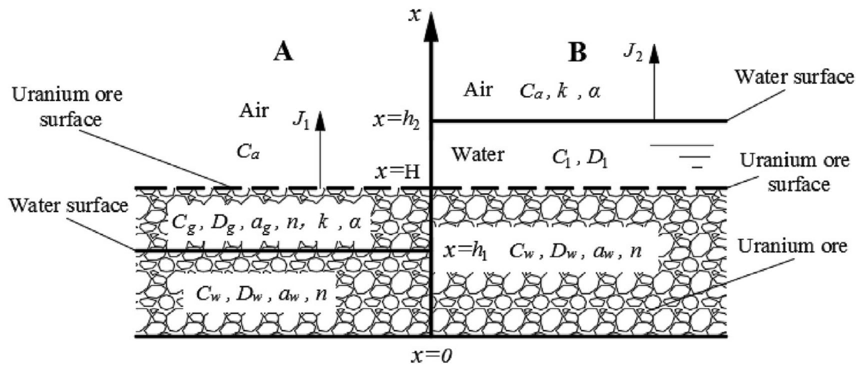

Fig. 1. Radon migration in the system. (A) water level lower than or equal to the fragmented uranium ore surface; (B) water level higher than the fragmented uranium ore surface.

In this study, we examined the influence of variations in water height in fragmented uranium ore to the surface radon exhalation rate by establishing a mathematical model and designing a one-dimensional, steady-state experimental apparatus. We first built the mathematical model of the diffusion of radon transport in a fragmented uranium ore containing water, then used the model to run a series of simulations. Next, we investigated the radon exhalation rate from the surface of fragmented uranium ore samples containing water. Finally, we verified the accuracy of the proposed numerical model for the quick prediction of the radon concentration and radon exhalation rate from fragmented uranium ore with various water levels based on our experimental measurements.

2. Modeling

2.1. Mathematical modeling and analytical solutions

Fig. 1 schematically depicts the physical model we used in laboratory environment, where radon emanates from the fragmented uranium ore with various water levels and then diffuses into the radon collector.

Here, we assume that radon migration in the fragmented uranium ore with various water levels is not affected by external factors (such as pressure and temperature) but only by diffusion in the liquid and air zone. The temperature of the entire system is constant, the content of radium in the water is negligible, and radon in the air-liquid interface has dissolution equilibrium. The ore system can be divided into two categories depending on the internal water level: Water level lower than or equal to the surface of the fragmented uranium ore (including 0 m water level) (Fig. 1A), and water level higher than the surface of the fragmented uranium ore (Fig. 1B). These two types of ore system must be modeled differently, so we used two cases to establish the mathematical model accordingly.

According to the calculation coordinates shown in Fig. 1, gas-liquid interface radon transfer theory (Kawabata et al., 2003), and Fick's law (Calugaru and Crolet, 2002; Webb and Pruess, 2003), we established a one-dimensional, steady-state mathematical model for radon migration at water level lower than the surface of the fragmented uranium ore (referred to from here on as "A") as shown in Eqs. (1)–(5):

$$D_w \frac{\partial^2 C_w}{\partial x^2} - \lambda C_w + \frac{a_w}{n} = 0, 0 \le x \le h_1 \tag{1}$$

$$D_g \frac{\partial^2 C_g}{\partial x^2} - \lambda C_g + \frac{a_g}{n} = 0, h_1 \le x \le H \tag{2}$$

$$D_w \frac{\partial C_w}{\partial x} = 0 (x = 0) \tag{3}$$

$$D_w \frac{\partial C_w}{\partial x} = D_g \frac{\partial C_g}{\partial x};\ C_w = \alpha C_g (x = h_1) \tag{4}$$

$$C_g = C_a (x = H) \tag{5}$$

where D_w is the radon diffusion coefficient in the liquid zone located in the uranium ore (m^2 s^{-1}); C_w is water radon concentration in the liquid zone located in the uranium ore (Bq m^{-3}); λ is the radon decay constant (2.1 × 10^{-6} s^{-1}); a_w is the free radon production rate for the uranium ore in the liquid zone (Bq m^{-3} s^{-1}); n is the void content in the uranium ore, (dimensionless); D_g is the diffusion coefficient of gas radon in the void in the ore (m^2 s^{-1}); C_g is gas radon concentration in the void (Bq m^{-3}); a_g is the free radon production rate for the ore in the void (Bq m^{-2} s^{-1}); h_1 is the water level (m) in the ore in the range [0, H]; α is the Ostwald coefficient; C_a is the background air radon concentration in the laboratory (Bq m^{-3}); and H is the height of the ore (m). The analytical solution to the radon transport equation for C_g and C_w can be obtained according to the given conditions based on Eqs. (1)–(5).

$$C_g = \frac{\sqrt{D_w}(a_w - \alpha a_g)\left(e^{A_6} + e^{-A_6} - e^{A_4} - e^{-A_4}\right)}{n\lambda\left[A_7\left(e^{A_2} + e^{-A_2}\right) + A_8\left(e^{A_1} + e^{-A_1}\right)\right]} + \frac{(C_a\lambda n - a_g)\left[A_8\left(e^{A_5} + e^{-A_5}\right) + A_7\left(e^{A_3} + e^{-A_3}\right)\right]}{n\lambda\left[A_7\left(e^{A_2} + e^{-A_2}\right) + A_8\left(e^{A_1} + e^{-A_1}\right)\right]} + \frac{a_g}{n\lambda} \tag{6}$$

$$C_w = \frac{\sqrt{D_g}\left[(\alpha a_g - a_w)\left(e^{B_2} + e^{-B_2} + e^{B_1} + e^{-B_1}\right)\right]}{n\lambda\left[(A_7)\left(e^{A_2} + e^{-A_2}\right) + (A_8)\left(e^{A_1} + e^{-A_1}\right)\right]} + \frac{\left[2\alpha(C_a\lambda n - a_g)\left(e^{B_3} + e^{-B_3}\right)\right]\sqrt{D_g}}{n\lambda\left[(A_7)\left(e^{A_2} + e^{-A_2}\right) + (A_8)\left(e^{A_1} + e^{-A_1}\right)\right]} + \frac{a_w}{n\lambda} \tag{7}$$