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A discrete model for prediction of radon flux from fractured rocks

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ABSTRACT

Prediction of radon flux from the fractured zone of a propagating cave mine is basically associated with uncertainty and complexity. For instance, there is restricted access to these zones for field measurements, and it is quite difficult to replicate the complex nature of both natural and induced fractures in these zones in laboratory studies. Hence, a technique for predicting radon flux from a fractured rock using a discrete fracture network (DFN) model is developed to address these difficulties. This model quantifies the contribution of fractures to the total radon flux, and estimates the fracture density from a measured radon flux considering the effects of advection, diffusion, as well as radon generation and decay. Radon generation and decay are classified as reaction processes. Therefore, the equation solved is termed as the advection-diffusion-reaction equation (ADRE). Peclet number (*Pe*), a conventional dimensionless parameter that indicates the ratio of mass transport by advection to diffusion, is used to classify the transport regimes. The results show that the proposed model effectively predicts radon flux from a fractured rock. An increase in fracture density for a rock sample with uniformly distributed radon generation rate can elevate radon flux significantly compared with another rock sample with an equivalent increase in radon generation rate. In addition to *Pe*, two other independent dimensionless parameters (derived for radon transport through fractures) significantly affect radon dimensionless flux. Findings provide insight into radon transport through fractured rocks and can be used to improve radon control measures for proactive mitigation.

1. Introduction

Radon gas is a major source of ionizing radiation (Nadakavukaren, 2011), emitting harmful radioactivity during its decay (McPherson, 1993). The Health Protection Agency (HPA) estimates that about 1100 radon-induced lung cancer deaths occur every year in UK (HPA, 2009), and the Environmental Protection Agency (EPA) estimates that about 21,000 radon-related lung cancer deaths occur each year in the US (US EPA, 2017). These problems are more severe around uranium-rich rocks (El-Fawal, 2011), because radon is a disintegration product from uranium (Barakos et al., 2014), known to be abundant in rare-earth minerals (Abumurad and Al-Tamimi, 2001). In addition, certain mining methods such as caving mining, which involves inducing fracturing of rock (McNearny and Abel, 1993; Li et al., 2014), increases rock's surface area and creates pathways for radon gas to migrate within the rock mass. This makes prediction of radon flux more complex in the caving mining of uranium-rich rocks.

Radon (discharged by radium-bearing molecules) migrates within the rock mass (Ferry et al., 2002) by diffusion and/or advection through pores, macro-pores, and fractures (Nazaroff and Nero, 1988; Ferry et al., 2002), and eventually emanates into the atmosphere. In a steady flow situation in a rock mass, fractures transport 99.99% of the total vertical mass flow through the composite medium (Nilson et al., 1991). Therefore, fractures contribute significantly to radon transport (Schery et al., 1982; Holford et al., 1993; Rowberry et al., 2016) and to proactively mitigating human exposure to radon. In this sense, knowledge of radon flux is required. At present, there are a few traditional approaches for predicting radon flux, but they are not relevant in all cases. One approach is the direct measurement of radon flux in houses and mines (Lario et al., 2005; Kitto, 2014; Ongori et al., 2015). For this approach, Lario et al. (2005) concluded that only uninterrupted

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short-term monitoring can represent radon concentration over an extended period. However, this approach is not relevant for rocks with access constraints, such as cave mines. Another approach used is laboratory investigation. Sahu et al. (2013) conducted a laboratory test of radon emanation rate from a low-grade uranium ore sample and found that in situ radon emanation rate is about 3 times higher than that measured in the laboratory. This disparity is attributed to the massive size and degree of fracturing in in situ orebodies (Bochiolo et al., 2012; Sahu et al., 2013), which is difficult to be replicated in laboratory studies. These challenges limit the application of these techniques. Hence, a non-traditional strategy is required to predict radon flux for large-scale underground excavations.

We developed an approach for predicting radon flux from fractured rocks, a discrete fracture network (DFN) model that can predict radon transport through fractures considering diffusion, advection, and radon generation with radon decay. We assumed that radon flux at the rock's surface is due to the transport by advection and diffusion (Catalano et al., 2015) through the fractures. Multiple studies predict that advection dominates radon transport (Nilson et al., 1991; Rowberry et al., 2016) (diffusion can be ignored); however, within the range of radon diffusion length (2.18 m) (Thompkins, 1982) and for rocks with low permeability, both are important (Bear et al., 1993; Mosley et al., 1996). The influence of diffusion transport is limited by its short half-life (3.83 d), but advection transport through structural discontinuities can cover about 100 m length more than diffusion (Appleton, 2013).

We solved the advection-diffusion-reaction equation (ADRE), where radon generation and decay are classified as reaction processes. This requires the knowledge of advection velocity (u) and we used three different methods to compute u. The technique developed in this study applies to fractured rock and specifically to instances such as a propagating cave mine, where the yield, seismogenic, and elastic zones (Board and Pierce, 2009; Sainsbury, 2010) (characterized by both natural and induced fractures) are inaccessible for field measurements.

2. Research approach

2.1. Radon flux

2.1.1. Radon flux from a rock mass

Advection and diffusion are the major transport mechanisms for a rock mass (Cigna, 2005; Prasad et al., 2012; Ye et al., 2014; Catalano et al., 2015). Therefore, radon flux (J) is obtained by summing the flux due to advection and diffusion. The flux due to diffusion (J_{diff}) is derived using Fick's first law of diffusion:

$$J_{\text{diff}} = -D\frac{\partial c}{\partial z} \tag{1}$$

and the flux due to advection (J_{adv}) is obtained (Garges and Baehr, 1998) using

$$J_{\text{adv}} = uc \tag{2}$$

where D is the radon's coefficient of molecular diffusion (m^2/s), c is the radon concentration (Bq/m^3), z is the fracture axis, and u is the advection velocity (m/s).

2.1.2. Radon concentration for a single fracture

Radon concentration (c), required for Eqs. (1) and (2), is obtained from radon transport equation (Bates and Edwards, 1980; Bear et al., 1993; Mosley et al., 1996:

$$\frac{\partial c}{\partial t} = \nabla\cdot(D\nabla c) - \nabla\cdot(Vc) - \lambda c + q \tag{3}$$

where λ is the decay constant (s^{-1}), t is the time (s), V is the fluid velocity (m/s), and q is the radon generation rate (Bq/(m^3 s)). For fractures in the rock mass, q is the radon flux from the fracture walls per unit aperture and is assumed to be uniform. Assuming a steady, incompressible and one-dimensional transport of radon along the fracture axis (z), Eq. (3) is reduced (Iakovleva and Ryzhakova, 2003; Xie et al., 2012; Zhang et al., 2014) to

$$D\frac{\partial^2 c}{\partial z^2} - u\frac{\partial c}{\partial z} - \lambda c + q = 0 \tag{4}$$

Eq. (4) is non-dimensionalized by using $c^* = c/c_\infty$ and $z^* = z/L$, where L is the characteristic length of the DFN size, and c_∞ is the reference concentration. Then we have

$$\frac{\mathrm{d}^2 c^*}{\mathrm{d}z^{*2}} - \frac{uL}{D}\frac{\mathrm{d}c^*}{\mathrm{d}z^*} - \frac{\lambda L^2}{D}c^* + \frac{L^2 q}{Dc_\infty} = 0 \tag{5}$$

The three dimensionless parameters identified from Eq. (5) are

$$\pi_1(Pe) = \frac{uL}{D} \tag{6}$$

$$\pi_2 = \frac{\lambda L^2}{D} \tag{7}$$

$$\pi_3 = \frac{L^2 q}{Dc_\infty} \tag{8}$$

where π_1 is the Peclet number (Pe), a parameter that relates the effectiveness of mass transport by advection to dispersion or diffusion (Fetter, 1993). It is used for classifying transport regimes (Garges and Baehr, 1998; Huysmans and Dassargues, 2005; Haddad et al., 2012; Chattopadhyay and Pandit, 2015; Yadav et al., 2016), and also as a stability measure in numerical analysis (Ewing and Wang, 2001). For $\pi_1 < 1$, diffusion governs transport, and advection is negligible (Huysmans and Dassargues, 2005). For numerical or analytical studies, knowledge of the dominant transport mechanism helps to eliminate a hyperbolic term related to advection or parabolic terms related with diffusion.

Using boundary conditions

$$c(0) = c_o \tag{9}$$

$$c(L) = c_L \tag{10}$$

for a fracture with length of L, the solution to Eq. (4) is obtained as

$$c(z) = \frac{\left[c_L - \frac{q}{\lambda} - \left(c_o - \frac{q}{\lambda}\right)\mathrm{e}^{\varsigma L}\right]\mathrm{e}^{\Gamma z} - \left[c_L - \frac{q}{\lambda} - \left(c_o - \frac{q}{\lambda}\right)\mathrm{e}^{\Gamma L}\right]\mathrm{e}^{\varsigma z}}{\mathrm{e}^{\Gamma L} - \mathrm{e}^{\varsigma L}} + \frac{q}{\lambda} \tag{11}$$

where $\Gamma = \frac{u}{2D} + \sqrt{\frac{u^2}{4D^2} + \frac{\lambda}{D}}$ and $\varsigma = \frac{u}{2D} - \sqrt{\frac{u^2}{4D^2} + \frac{\lambda}{D}}$.

For clarity on the boundary conditions, Fig. 1 shows a schematic of a fractured rock with an arbitrarily located single fracture with the length of L, along the fracture axis (z). In this case, either end of the fracture can be c_o or c_L. If the flux is negative, then the transport direction is opposite to the assigned direction.

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