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Radon dispersion modeling and dose assessment for uranium mine ventilation shaft exhausts under neutral atmospheric stability

Dong Xie [a,b,*], Hanqing Wang [c], Kimberlee J. Kearfott [d], Zehua Liu [b], Shunquan Mo [b]

[a] School of Energy Science and Engineering, Central South University, Changsha 410083, China
[b] School of Urban Construction, University of South China, Hengyang 421001, China
[c] School of Civil Engineering, University of Hunan Technology, Zhuzhou 412007, China
[d] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109-2104, USA

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ABSTRACT

In the present study, the roles of atmospheric wind profiles in the neutral atmosphere and surface roughness parameters in a complex terrain were examined to determine their impacts on radon (^{222}Rn) dispersion from an actual uranium mine ventilation shaft. Simulations were completed on ^{222}Rn dispersion extending from the shaft to a vulnerable distance, near the location of an occupied farmhouse. The eight dispersion scenarios for the ventilation shaft source included four downwind velocities (0.5, 1.0, 2.0 and 4.0 m s^{-1}) and two underlying surface roughness characteristics (0.1 m and 1.0 m). ^{222}Rn distributions and elevated pollution regions were identified. Effective dose estimation methods involving a historical weighting of wind speeds in the direction of interest coupled to the complex dispersion model were proposed. Using this approach, the radiation effects on the residents assumed to be outside at the location of the farm house 250 m downwind from the ventilation shaft outlet were computed. The maximum effective dose rate calculated for the residents at the outside of the farm house was 2.2 mSv y^{-1}, which is less than the low limit action level of 3–10 mSv y^{-1} recommended by the International Commission on Radiological Protection (ICRP) occupational exposure action level for radon.

1. Introduction

Radon (^{222}Rn) emitted from uranium mine ventilation shaft exhausts could constitute a major source of environment contamination and consequently a potential health hazard to the nearby population. Due to their alpha-emitting short lived progeny ^{218}Po and ^{214}Po, ^{222}Rn have long been recognized as main causative agent for lung cancer when presented in high radon inhalation, such as those encountered in uranium mining areas (Evans et al., 1981). The geographical features of the dispersion region and the meteorological conditions are important for evaluating the dispersion of ^{222}Rn from uranium mine shaft exhausts. Essential parameters to be considered include the ^{222}Rn emission concentration as it leaves the shaft, gas emission velocity, shaft location and height, trees and topography, wind speed and direction, atmospheric stability (Bruce and Werner, 1990) and precipitation.

Full-scale field measurements, wind tunnel experiments, and computational fluid dynamics (CFD) models have been used to study pollutant dispersion for complex underlying surface conditions. For some field measurement situations, it is hard to simultaneously control operative and intertwined parameters effects (Ana Pilar et al., 2002) such as atmospheric conditions (wind speed, wind direction), topography and geography (underlying surface roughness, mountain height and shaft height, width, shape). The need to utilize hazardous radioactive sources and also the difficulties in creating appropriate boundary conditions similarity may limit the efficiency of wind tunnel experiments (Sharma et al., 2005). However, CFD works well for this situation. CFD has been proved to be a very powerful and efficient tool for the studies of radionuclides dispersion with the factors considered individually or in combination with the wind field effect (de Sampaio et al., 2008). Several previous studies have involved simulations of the atmospheric dispersion of nuclear power plant (NPP) emissions (Srinivas and Venkatesan, 2005; Basit et al., 2008), including from the Chernobyl (Hiroaki and Masamichi, 2008) and Fukushima accidents (Leelössy et al., 2011). ^{222}Rn concentration dispersion and the effective dose evaluation obtained in this study differ from the NPP work not only due to the different radionuclide, but because the

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* Corresponding author. School of Urban Construction, University of South China, Hengyang 421001, China. Tel.: +86 734 828 2512; fax: +86 734 828 2312.
E-mail address: nhxiedong@126.com (D. Xie).

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release was continuously from a low height and the topographical and geographical features and surrounding the release are very different, namely in mountainous rural terrain.

Little information was available in the literature about the numerical analysis of ^{222}Rn dispersion and dose evaluation of ^{222}Rn from uranium mine ventilation shafts. Some CFD modeling of the situation has been finished, but it was limited to a single location. This work did, however, included field measurements that provided solid validation for CFD modeling of this problem (Dong et al., 2012). In current study, ^{222}Rn dispersion under neutral atmospheric stability conditions was analyzed using three-dimensional CFD simulation for a specific area above a uranium mine in one province of China. This particular location included an occupied home and farmed area around it. CFD modeling was accomplished using Fluent (Ansys Fluent, 2010), a commercially available and widely used tool incorporating several turbulence models (ANSYS Fluent 13.0.0, ANSYS Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317 USA). ^{222}Rn distributions and elevated pollution regions in the surrounding area of uranium mine ventilation shaft were calculated. For this case, public effective dose rate calculation methods were developed and radiation dose rate to the farmers living and working in the vicinity of a house 250 m downwind from the shaft was evaluated.

2. Models and computational methods

2.1. Geometric model

The geometric model considered in this study was based upon an actual ventilation shaft located in uranium-bearing mountains in China. Discrete data points for the model were extracted from an elevation contour map and processed with specialized Fluent preprocessing software, Gambit (Ansys Fluent, 2010). The overall computational dimensions of mountain were 400.0 m (L) × 400.0 m (W) × 150.0 m (H) in the X, Y and Z directions, respectively. The ventilation shaft outlet was modeled to match its actual dimensions of 2.7 m × 2.7 m, extending 2.0 m above the ground's surface. In the present study, Temperature of the exhaust is set to be the same as the atmosphere because of neutral atmospheric stability and large amount of exhaust air rate. ^{222}Rn was emitted from uranium mine ventilation shaft at a certain flow rate of 3.0 m s^{-1}, then mixed with air and dispersed in three directions into atmosphere as shown in Fig. 1a.

2.2. Mathematical models

Considering that the atmospheric temperature could be regarded as homogeneous with heights in the computation region under the neutral atmospheric stability, CFD simulation was based on the governing equations of continuity, momentum, pollutant transport, turbulent energy and turbulent dissipation rate, as shown in Table 1. Xiaomin et al. (2005) investigated the influence of complex geometry on pollutant dispersion comparing different k–ε models with wind tunnel measured data for optimization of turbulence models. Their comparison results show that the standard k–ε model provides the best simulation results (Brian and Dudley, 1974), while Renormalization Group (RNG) k–ε turbulence models based on RNG theory (Victor and Steven, 1986) and modified k–ε turbulence models (Chen and Kim, 1987) over-predict the pollutant concentrations. Standard k–ε closure was thus chosen as the turbulence model in this study. The parameters of equations (1)–(6) depicted in Table 1 are defined as: X is the coordinate axis in the direction i ($i = 0, 1, 2$), u_i corresponds to the mean velocity in i direction, ρ is the air density, t is time, P is pressure, μ_t is the turbulent viscosity, μ is the molecular viscosity, and g is the gravitational acceleration. K is the turbulence kinetic energy, and ε is the dissipation rate of turbulence kinetic energy. C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, and σ_ε are empirical and experimental constants fixed as 0.09, 1.44, 1.92, 1.0, and 1.3, respectively (Brian and Dudley, 1972). C is the ^{222}Rn average concentration in the air, u is the velocity vector of the ^{222}Rn, D is the effective diffusion coefficient of ^{222}Rn in air assigned a value of 5×10^{-3} m^2 s^{-1}, which is from the work of Guo (Qiuju et al., 1995), λ is the radon decay constant equal to 2.1×10^{-6} s^{-1}.

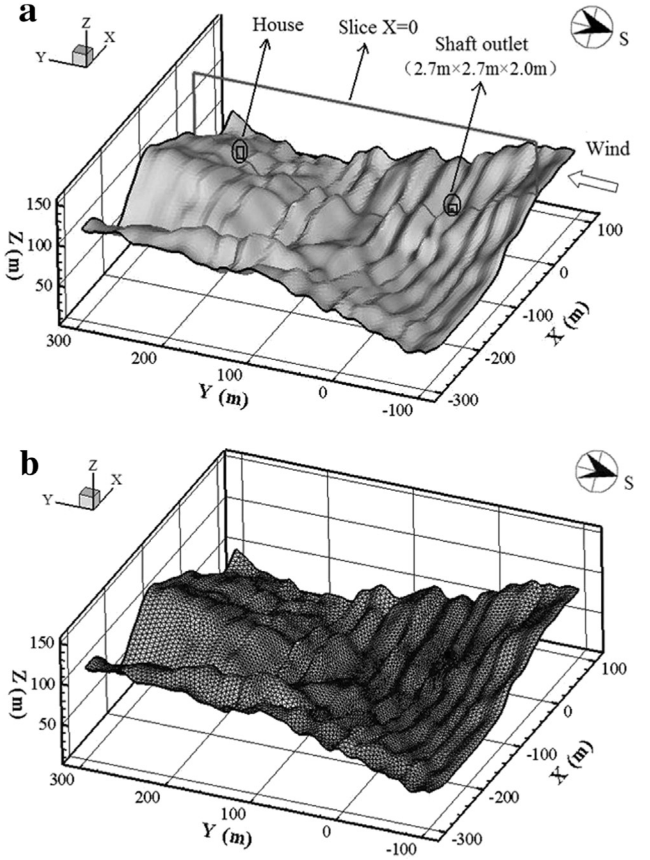

Fig. 1. Fig. 1a. Map of surface above uranium mine showing actually topographic details, including the location of the shaft and the house (250 m downwind), along with the computational slice $X = 0$ and the southerly wind direction perpendicular to the $Y = 0$ plane. Fig. 1b. Unstructured computational grid used for finite volume analysis for the CFD model of the actual topographic surface.

2.3. Numerical codes and solution methods

CFD modeling was conducted with the code Fluent in this paper. The simulation involved the finite volume discretization of the equations of motion, a geometrical model consisting of an unstructured grid volume made of tetrahedral cells, various matrix-inversions routines, and the k–ε turbulence model (Jie et al., 2009). The coupling between velocity and pressure was accomplished through the SIMPLE algorithm (Patankar, 1980). The central differencing scheme was used in diffusion term and advection term, while an upwind differencing scheme was used in source term.

In such a complex terrain area, the unstructured grid system is the most efficient for CFD simulations (Hong et al., 2005), so this approach was selected. The computational domain was built using tetrahedral cells with a finer resolution nearest the ventilation shaft outlet and the mountain ground surface. In the CFD model, a non-uniform tetrahedral grid of approximately 370,000 cells was