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Research article

Theoretical modeling of indoor radon concentration and its validation through measurements in South-East Haryana, India

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ABSTRACT

A three dimensional semi-empirical model deduced from the existing 1-D model has been used to predict indoor radon concentration with theoretical calculations. Since the major contributor of radon concentration in indoors originates from building materials used in construction of walls and floor which are mostly derived from soil. In this study different building materials have been analyzed for radon exhalation, diffusion length along with physical dimensions of observation area to calculate indoor radon concentration. Also calculated values have been validated by comparing with experimental measurements. The study has been carried out in the mud, brick and cement houses constructed from materials available locally in South-East region of Haryana. This region is also known for its protruding land structure consisting volcanic, felsite and granitic rocks in plane. Further, exhalation (J_w) ratio from wall and floor comparison has been plotted for each selected village dwelling to identify the high radon emanating source (building material) from the study region. All those measured factors might be useful in building construction code development and selection of material to be used in construction.

1. Introduction

Considerable development has been observed in the field of radiation detection and measurement from past decades. Each day with increasing health awareness, more sophisticated scientific instruments have been developed to improve the radionuclide detection studies. Radionuclide such as, radon (^{222}Rn) and its progeny is major contributor in indoor radiation as it is found to be around 55% of the total radiation dose received by the population on earth from natural environment (UNSCEAR, 2000). Therefore, it is important to understand its origination and migration in indoors for health hazard purpose. ^{222}Rn itself is not hazardous as it is cleared quickly as it is absorbed but its short lived daughter elements Polonium isotopes (^{212}Po and ^{214}Po) can be hazardous, if stick in lungs and interact with soft tissues may lead to lung cancer (Krewski et al., 2005; Singh et al., 2015). Serious health issues have been observed in poorly ventilated buildings which were designed without taken care of factors such as origin of raw material from which building material has been derived and radon mitigation process. Therefore the major focus should be given in building design codes and control systems to minimize radon levels in indoors (Rahman and Tracy, 2009; Scivyer, 2001). Numerous studies have been done so far to find out radon exhalation rate from building materials, bricks, concrete, gravel and marble using various instruments like solid state nuclear track detector (SSNTD) based can technique and Rad7 based methods etc (Chen et al., 2010; Saad et al., 2013; Sahoo et al., 2011). It has been concluded from these studies, radon exhalation (flux) from building material and soil are the primary cause of radon build up in indoors.

In the present study, indoor radon concentration calculations were carried out in the selected dwellings which were mainly composed of mud and wood as building material. We have followed the theoretical models which have been suggested recently in the literature for prediction of indoor radon concentration from exhalation rates of building materials. Further predicted results of various models have been compared and validated with experimental observation. Although in actual practice, the variation in radon exhalation from wall depends upon the value of radon diffusion length due to thickness of wall, density and dimensions of the building material used for its construction and on the observation process (Sahoo et al., 2011). Therefore, physical change in the matrix during wall, floor and roof construction is considered negligible during radon concentration calculations from observed

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radon exhalation rate of building material samples. Hence, generation and transport process of radon in walls might be slightly different in actual conditions than assumed ones.

In theoretical calculations, we have considered 1-D model by Nazaroff and Nero (1988) which contains radon emanation factor, radium content and radon diffusion length of building material. The given 1-D model equation has been modified using radon mass exhalation equation by Sahoo et al. (2007). Another semi-empirical model has been followed, which account radon flux emission from all the faces of building material given by Sahoo et al. (2011) is also known as 3-D. Radon diffusion length and radon surface exhalation flux from building materials has been used as input parameters for radon flux prediction from wall. In this model, ratio of exhalation rates from wall and building material (J_w/J_B) with respect to the diffusion length (l) has been deduced as a major inferring factor in flux prediction. The factor S_Bd/V_B deduced from ratio of varying diffusion length with respect to the ratio (J_w/J_B) in 3-D model is similar to the correction factors suggested by Stoulos et al. (2003). Our focus mainly subjected to provide appropriate, efficient and reliable method to predict indoor radon concentration without halting progress in the construction process while comparing modeling techniques and validating theoretically predicted results with experimental observations.

This paper is organized as follows: In section 2 we present the theory of different models such as: Nazaroff and Nero, Stoulas et al. and Sahoo et al. models. This follows the brief description of methods for calculation of indoor radon concentration from exhalation rates of various building materials. In section 3 experimental setups and methodology detail has been given for measurement of exhalation rate using scintillation radon monitor (SRM). Description of Pin cup hole dosimeter used for measurement of indoor radon concentration also given in this section. Results of indoor radon concentration derived from modeling and measurements given in section 4 with comparative analysis.

2. Methods of calculation

2.1. Description of theoretical models

Most commonly used method for the estimation of radon flux in building's indoor is the solution of 1-D radon diffusion equation. Various input parameters such as radium content, radon emanation factor, radon diffusion length and density of building material has to be calculated first. Then observed input parameters have been used in the solution of 1-D radon diffusion equation suggested by Nazaroff and Nero (1988) to carry out radon flux from wall (J_w).

$$J_w = \gamma \times \lambda \times \varepsilon \times \rho \times l \times \tanh(d/l) \quad (1)$$

where, J_w is radon flux from wall or floor (Bq kg^{-1} hr^{-1}), γ radium content in the building material (Bq kg^{-1}), λ the radon decay constant (hr^{-1}), ε is the radon emanation factor depends upon moisture content in building material, ρ density of building material (kg m^{-3}), l is radon diffusion length through materials and d is the half thickness of wall (m). To identify so many input parameters is tedious work so we have reduced Equation (1), by considering radon atom reaching pore volume escapes totally into the chamber volume of the sampling setup, therefore radon mass exhalation rate can be written as (Sahoo et al., 2007).

$$J_m = \gamma \times \lambda \times \varepsilon \quad (2)$$

where, J_m is radon mass exhalation (Bq kg^{-1} hr^{-1}).

After substitution of Equation (2) in Equation (1) we have got the final solution of equations,

$$J_w = J_m \times \rho \times l \times \tanh(d/l) \quad (3)$$

Equation (3) is reduced form of Equation (1), which alternatively could compensate various input parameters by assuming no loss in flux detection in experimental setup while mass exhalation measurements.

Another model suggested by Sahoo et al. (2011), in which radon flux from wall can be predicted by measuring surface exhalation rates from building material (J_B) (Bq m^{-2} hr^{-1}). This model can be used for prediction of both ^{220}Rn (thoron) and ^{222}Rn (radon) as it's based on diffusion length. Although in case of ^{220}Rn the diffusion length in the materials is much smaller than half thickness of wall, i.e. $l << d$, then relation between exhalation rates measured for wall by two models have same value as that of exhalation rates measured from building material.

$$J_w/J_B = 1$$

But, In case of ^{222}Rn (radon) the diffusion length is much larger than the half thickness of the materials i.e. $l >>$ d, then ratio of exhalation from wall to the building material (J_w/J_B) accounts surface area, bulk volume and thickness of building material directly proportion in radon emanation with simple expression shown as,

$$J_w/J_B = S_B d/V_B$$

By using comparative empirical extrapolation of 1D and 3D model a simple model Equation (4) has been derived from several possible fitting functions which are in agreement of above limiting condition and given as (Sahoo et al., 2011).

$$J_w/J_B = (S_B d/V_B - 1)exp(-kd/l) + 1 \quad (4)$$

whereas S_B represents surface area and V_B is bulk volume of building material and k is regression constant estimated to be 0.31 ± 0.05 (Sahoo et al., 2011).

After calculating radon exhalation from wall, indoor radon concentration can be estimated by series of calculation using equation given below.

$$C_R = \sum_k (J_{wk} \cdot S_k / V \cdot (\lambda + \lambda_v)) \quad (5)$$

where, J_{wk} is radon exhalation from wall or floor and S_k represents the surface area of room inside with ($\lambda+\lambda_v$) as effective radon removal rates in V volume of room.

We have also used the formula for estimation of radon concentration suggested by Stoulos and his co-workers (Stoulos et al., 2003), which includes, surface fractional radon exhalation from building material as given by Equation (6),

$$C_R = \left[\sum_k E_{wk} \cdot F_{wk}\right] \cdot (S/V \cdot \lambda_v) \quad (6)$$

where, E_{wk} is the surface exhalation rate in (Bq m^{-3} hr^{-1}) and F_{wk} is surface fractional usage of building material in S/V surface to volume ratio of the room with λ_v annual average room ventilation rate (hr^{-1}).

3. Experimental technique

3.1. Indoor radon concentration measurement

The validation of theoretically observed results has been carried out by using "pin-holes based twin cup dosimeter" technique in the selected dwellings of the study region. It has single face entry for