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Impact from indoor air mixing on the thoron progeny concentration and attachment fraction

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A B S T R A C T

Despite the considerable amount of work in the field of indoor thoron exposure, little studies have focussed on mitigation strategies to reduce exposure to thoron and its progeny. For this reason an advanced computer model has been developed that describes the dispersion and aerosol modelling from first principal using Computational Fluid Dynamics. The purpose of this study is to investigate the mitigation effects from air mixing on the progeny concentration and attachment with aerosols. The findings clearly demonstrate a reduction in thoron progeny concentration due to air mixing. The reduction in thoron progeny is up to 60% when maximum air mixing is applied. In addition there is a reduction in the unattached fraction from 1.2% under regular conditions to 0.3% in case of maximum mixing.

1. Introduction

For long it has been assumed that the contribution from thoron progeny to the total exposure from radon isotopes was limited to around 10% (UNSCEAR, 2006). However, experimental studies (Doi et al., 1994; Bochicchio et al., 1996; Ma et al., 1997) have demonstrated that exposure to thoron may well exceed that of radon. Although the exposure varies greatly and depends on used building materials, thoron exposure cannot be ignored (Steinhäusler, 1996).

Contrary to radon, the thoron concentration varies considerable within the living room making a dose assessment more difficult to perform. This is mainly due to thoron's short half-life of 56 s. As a result high concentrations are found near the building materials, while in the centre of the room the thoron concentrations are comparatively low. This makes an adequate dose assessment far more challenging as compared with radon, where the radon gas concentration is perceived as a measure for the hazardous progeny.

At present a respectable piece of work has been reported on thoron progeny products both on the experimental side as well as the computer modelling. The use of computer modelling for this application has been first reported by Jacobi (1972) and Porstendörfer et al. (1978). However, these studies assumed a homogeneous activity distribution in the room. More recent studies (Zhuo et al., 2001; Urosevic et al., 2008) have addressed this shortcoming, using numerical simulation. Nevertheless, in those simulations the attachment of thoron progeny to aerosol particles as well as its deposition has been simplified.

In recent years also advanced Computational Fluid Dynamics (CFD) models have been developed to model the dispersion of thoron (Chauhan et al., 2015) and its progeny as well as the attachment and deposition of the progeny nuclides (De With and De Jong, 2011).

On the experimental side studies on thoron and thoron progeny concentrations in climate chambers and dwellings have been performed (Li et al., 2012; Sorimachi et al., 2015; Janik et al., 2013), using various kinds of measurements techniques. Despite this, little studies have focussed on mitigation strategies to reduce exposure to thoron and its progeny (Vanmarcke, 1996; Wang et al., 2012). Such mitigation can focus on various parts of the exposure chain. Stage one is to reduce the thoron source, by means of selecting materials with a low ^{228}Th content or by selecting materials with low thoron emanation. Stage two is the use of barriers to prevent the release of thoron in the habitable space. Typical examples here are the use of seals and coatings. Stage three is to reduce the thoron gas concentration. Although it must be stated that such step is mostly relevant for radon and less applicable for thoron due to its short half-life. Finally stage four is to reduce the concentration of

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the hazardous progeny. This can be achieved e.g. by cleaning the air through enhanced deposition or the use of cleaning devices.

Most regulatory requirements on building materials are focused on source reduction by setting requirements on activity concentrations (EC, 2013) and exhalation rates if radon is considered e.g. ÖNORM (1998) that takes account of the radon exhalation rate. Mitigation strategies for radon in existing dwellings are focused on the application of barriers and reducing gas concentrations by means of effective ventilation. Mitigation by means of reducing the progeny concentrations directly is less common.

Previous work carried out by De Jong and Van Dijk (1995, 2002) and Maher et al. (1987) has focussed on the efficacy of such mitigation strategies as listed under stage four. The work was specific to ^{222}Rn, but demonstrated considerable reduction in progeny concentrations when using enhanced recirculation and air cleaning devices based on ionising of the air. The reductions in radon progeny ranged from 10 to even as much as 90%. The largest reductions were mostly achieved with regular commercial air cleaning devices; however, also the use of enhanced air mixing resulted in a significant reduction. Similar effects have also been reported by others (Rudnick et al., 1983; Bigu, 1983; Maher et al., 1987; Kozak et al., 2014), who observed a significant decrease in radon progeny of around 40% when air-mixing fans were used.

The purpose of this computational study is to understand the effects of such mitigation measure on the thoron progeny concentrations and its attachment with aerosols. For this reason the proposed CFD model is first compared against radon measurements from the in-situ test facility described by De Jong and Van Dijk (1995, 2002). As part of the experimental work, measurements on radon, radon progeny as well as the attached fraction are carried out.

Subsequently the model is applied to thoron, first for a scenario without any mechanically driven internal air recirculation followed by a total of three air recirculation scenarios. Thoron and thoron progeny concentrations as well as attachment fractions are obtained from the computation and used to assess the efficacy of this thoron mitigation approach.

2. Model approach

In this work a CFD model is developed to simulate the concentration of thoron and thoron progeny products in a typical Dutch living room. The dispersion is computed using the fundamental flow equations for gas and aerosols, which enables detailed simulation of the three-dimensional flow structures from ventilation and buoyancy. Extra algorithms are developed and coupled with the CFD model to take account of all relevant physical processes. These include the formation and attachment of the progeny products to aerosol particles as well as the dispersion and deposition of the radioactive aerosols.

2.1. Airflow modelling

Simulation of the airflow is based on the conservation equations for mass, momentum and energy. The mass conservation equation is defined in the following manner:

$$\rho(\nabla\cdot u_k) = 0, \tag{1}$$

where ρ is the density of air (kg m^{-3}); u is the velocity vector (m s^{-1}) and k is the index for the three velocity components. The momentum equation for incompressible air reads:

$$\rho\left(\frac{\partial(u_k)}{\partial t} + \nabla\cdot(u_k u_l)\right) = -\nabla P + \nabla\cdot(\mu_e \nabla u_k) + S_{u,k}, \tag{2}$$

where P is pressure (N m^{-2}); μ_e is the effective viscosity (N s m^{-2}) and S_u is the source term (N m^{-3}). The index l is used to indicate the three velocity components. The airflow in the room is considered turbulent and therefore turbulent flow movements are taken into account using the k-ε turbulence model. Consequently, the effective viscosity μ_e is the sum of the dynamic viscosity of air μ_l and the turbulent viscosity μ_t computed by the k-ε turbulence model (Launder and Spalding, 1974).

The heat dispersion is computed using the conservation equation for energy, which reads:

$$\frac{\partial \rho E}{\partial t} + \nabla\cdot\rho u_k E = -\nabla u_k P + \nabla\cdot(\Gamma_T \nabla T), \tag{3}$$

here E is the total energy per unit mass (J kg^{-1}); T is the absolute temperature (K) and Γ is the diffusion coefficient (m^2 s^{-1}). The diffusion coefficient (Γ) in the dispersion calculation is based on the effective viscosity (μ_e ρ^{-1}) in the momentum equation (Hinze, 1975).

2.2. Modelling of thoron

For the dispersion of thoron gas an additional conservation equation is applied. This conservation equation can be described as:

$$\frac{\partial C_{Tn}}{\partial t} + \nabla\cdot u C_{Tn} = \nabla\cdot(\Gamma_{Tn} \nabla C_{Tn}) - \lambda C_{Tn}. \tag{4}$$

In this equation C is the activity concentration (Bq m^{-3}) and Γ is the diffusion coefficient (m^2 s^{-1}) of thoron. The two terms on the left hand side represent the convective transport of activity. On the right hand side the dispersion from diffusion is shown followed by a sink term to represent nuclear decay from thoron. In this equation λ is the decay constant of thoron (s^{-1}).

2.3. Modelling of thoron progeny

The progeny products from thoron attach to water molecules and other polarized molecules in the air to form ultra-fine radioactive clusters. Those clusters are formed within less than one second and have a diameter of 0.5–5 nm. Most of those clusters will attach rapidly to the ambient aerosols, creating radioactive aerosols with a diameter of around 10 nm–10 μm (Porstendörfer and Mercer, 1979). Due to the formation of those clusters and the attachment with aerosols the dispersion cannot be considered a gas; hence, equation (4) no longer holds. For the dispersion of aerosols a modified conservation equation is required. The proposed equation is based on the drift-flux method described by Lai and Nazaroff (2000). In this method the dispersion of particles can be written as:

$$\frac{\partial C_n}{\partial t} + \nabla\cdot\left[(u + v_{s,n})C_n\right] = \nabla\cdot[(\Gamma_n + D_n)\nabla C_n] - \lambda C_n - v_d \frac{\partial C_{b,n}}{\partial y}. \tag{5}$$

Here the convective transport is based on a modified flow field. In this flow field the terminal velocity v_s (m s^{-1}) of the particles is incorporated. The index n is used to identify the various progeny nuclides simulated in this work. In addition the Brownian diffusion coefficient D (m^2 s^{-1}) is added to the effective diffusion. This diffusion coefficient is described by the Einstein–Cunningham equation: