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A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents

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ABSTRACT

Sudden large scale outdoor releases of toxic materials may require protective actions in the affected areas, and one option is to shelter indoors. Mechanically ventilated buildings provide protection against outdoor hazardous particulate materials with varying efficiency depending mainly on the properties of the HVAC system of the building, air leakage, and the nature of the outdoor release. A tool for modelling the indoor concentrations due to outdoor contaminants has been developed and presented. The tool solves numerically the simplified mass balance equation describing the size-resolved behaviour of airborne particles and uses as input experimentally obtained data on particle concentrations outdoors, in the supply air, and indoors. By eliminating the effect of indoor sources the size-resolved indoor/outdoor (I/O) ratio for fine particles can be determined accurately, thus giving detailed information on the buildings protective capability and thereby quantitative knowledge to support emergency managers decision making.

1. Introduction

In order to protect communities from intentional or accidental releases of toxic materials questions we should at least consider are: what steps should we take to prepare for these kinds of incidents and, if necessary, how to respond to them? Furthermore, should we, for example, come back to the idea of common public shelters dedicated to the civilian population which was one of political priorities of most governments back to the times of the Cold War? The issue is still being discussed in many countries. However, the point is that due to the common uncertainty and dynamism of changes we experience in todays' world, the threats could come rapidly enough to not give us a chance to realise them; to localise a shelter and finally get to a public shelter. In many cases these shelters are far away from the place we live in or do not exist at all in close proximity. This hypothesis is confirmed by official reports which in some countries state that there is a very limited number of available places in public shelters to be used in case of a disaster or a war. For example in one of the central European countries there is only 2.9% available sheltering places of overall number of population [1]. This could bring us to the next question. Should we really consider these public shelters as an effective way of protecting the population? Shouldn't we rather focus on the protection strategy which assumes that everybody can protect themselves in the place where they in at the moment of the chemical or radiological incident, e.g. in a family house or public building. If so, what should we know about the appropriate behaviour and what is the real threat of contamination for us if we stay in this building when the incident happens? And finally, how much of dangerous materials can be transmitted from outside to inside the building?

In the event of large scale outdoor releases of hazardous materials the two primary measures to protect the public health from excessive exposure are thus mass evacuation of people from affected areas or sheltering indoors. In the sheltering option, people are typically advised to "go in, stay in and tune in [2]", close doors and windows, shut off ventilation and turn on radio for further instructions. In more detailed guidelines it is advised not to use elevators because they create a piston effect and can pump air into or out of the building, have people gather in pre-identified "shelter-in-place" rooms that have no or low air exchange with the outdoors, and have low air exchange with the rest of the building [3].

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Once the outdoor concentration has diminished to safe levels, the building should be evacuated or flushed with outdoor air. The protection can be improved with high-efficiency supply air filtration and proper operation of the HVAC system.

The main factors affecting buildings protection efficiency against outdoor toxic agents are the duration of the event and the infiltration of contaminants. The event duration depends on the source. Accidental leaks from tanks can be over or under control within few hours while during the Fukushima and Chernobyl nuclear power plant disasters the release continued for several days. The contaminant transport rate from outdoors to indoors depends both on the building and toxic material characteristics. In general, airtight buildings provide better protection than leaky ones for short term releases, and the building envelope generally removes coarse particulate materials but not significantly gaseous agents with high vapour pressure.

Since a key parameter in outdoor pollutant penetration is air exchange between the indoor and outdoor environments, several studies have been conducted to estimate the infiltration and natural ventilation rates. In an extensive investigation Langer et al. [4] used occupant-generated carbon dioxide as tracer gas to determine the nighttime air exchange rate of 450 French dwellings and found the average value to be 0.65 1/h with a standard deviation of 0.87 1/h. Taylor et al. [5] studied the effects of building characteristics and occupational behaviour on the I/O ratio of outdoor PM2.5 using building archetypes representative of Greater London area. For calculating the infiltration they used the EnergyPlus building simulation tool assuming penetration for PM2.5 to be 0.8 when windows were closed and 1.0 when open. The modelled I/O ratios varied from 0.37 to 0.74 and were lowest in low permeability houses in wintertime and highest in scenarios in summertime when windows were opened for cooling.

There have been also experimental studies of the effect of ventilation type on indoor air pollutant levels. Irga and Torpy [6] measured indoor concentrations of several contaminants in eleven different office environments in Sydney throughout one year and found clear correlation with the ventilation type and level of contaminants. The pollutant levels, including particles, were in general lowest for buildings with mechanical ventilation.

Shelter in place has also been advised to be taken as an action for public health protection during the Southeast haze episodes. Chen et al. [7] examined the indoor and outdoor size resolved particle concentrations in a typical mechanically ventilated office building during and after the 2013 haze in Singapore, and found a clear relationship between the characteristics of the ventilation system and I/O ratio of particles in the size range of 0.3–1 μm. In another study [8] the positive pressure control method was analysed by modelling using various environmental parameters and building characteristics. It was concluded that the influences of outdoor wind velocity and the leakiness of the building on preventing the entry of the outdoor particles with positive pressure control are relatively dominating. The researchers also found that for a building equipped with fibrous supply air filters, particles in the size range of 0.1–0.3 μm have the highest penetration. The indoor air cleaning method which allows outdoor particles to enter indoors first and the uses filtration to remove them, was found to be increasingly more effective with decreasing supply air filtration efficiency and building air tightness. Ward et al. [9] concluded that a representative room air cleaner in a typical US house would reduce the indoor concentration of outdoor originated particulate contaminants by 40–60% in the size range of 0.1–2 μm.

Several models have been developed to calculate sheltering efficiency of buildings. Siren [10] calculated infiltration air flows and contaminant transport inside a residential building assuming a gaseous contaminant. Jetter and Whitfield [11] determined the protection factor for a room inside a test house for various scenarios. Chan et al. [12] utilised the data from US house leakage measurements to evaluate sheltering efficiency under different chemical release scenarios. In his dissertation thesis Chan studied also the protection provided by commercial buildings with the mechanical ventilation system running [13]. In these studies it has been assumed that the duration of the incident is relatively short, up to few hours. Engelmann [14] determined a dose reduction factor (DRF) for airborne contaminants as the ratio of time-integrated airborne concentrations indoors and outdoors, and demonstrated that for long duration plumes containing respirable plutonium the DRF approaches the equilibrium indoor/outdoor ratio for particulates.

A significant fraction of radionuclides released by nuclear incidents such as nuclear reactor accidents are in the form of radioactive particles. Measurements demonstrated that after the Fukushima accident the air contained radioactive particles with activity median aerodynamic diameter (AMAD) ranging between 0.25 and 0.71 μm for ^{137}Cs, from 0.17 to 0.69 μm for ^{134}Cs, and from 0.30 to 0.53 μm for ^{131}I [15]. These are similar to the findings made after the Chernobyl accident [16,17]. Although during the Fukushima incident the airborne radioactive particles were of no concern for public health in Europe because of atmospheric dispersion and dilution along the route from Japan, the Chernobyl disaster demonstrated that the activity of particles can be orders of magnitudes higher [15–17].

In order to be able to make informed decisions the emergency response planners should be able to predict the protection capability of buildings against outdoor hazardous particles more accurately. This has been noted by Sohn et al. [18] who presented a screening level methodology by which generalised information about airborne concentrations and building occupant exposures can be predicted as a result of a pollutant release to assist decision makers in developing generic plans and responses. They also demonstrated how the lack of building specific information can result in wide uncertainties in exposure prediction.

The key factors affecting the estimation of predicted dose are the concentration and duration of the plume at a particular location, and the penetration of outdoor contaminants to indoors. Prediction of release durations is difficult because of the wide range of potential incidents. Therefore, planners should consider the possibility that the duration of a release may range from less than 1 h to several days.

Although several models have been developed for calculating the indoor contamination level due to outdoor pollutants there are still large uncertainties in the analysis results because of the uncertainties associated with the key parameters. Accurate determination of indoor to outdoor concentration ratios is challenging due to temporal variations of outdoor pollutant levels, and also due to indoor sources. The aim of this study was to develop an indoor contamination model for a mechanically ventilated building, present an experimental measurement system for determining the some of the key parameters which, when combined with information about the building and HVAC system characteristics, give the sheltering efficiency and to validate the model's performance in real-world conditions. The validation was made using ambient fine particles as simulants for outdoor contamination.

2. Model

Sheltering efficiency depends on several factors like the characteristics of the threat agents, mechanical ventilation flow rate and air filtration, and infiltration of outdoor air into buildings. A schematic of the simplified building model used in this study is shown in Fig. 1. Outdoor contaminants enter the building through the