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Visual assessment of contaminant impacts in multizone buildings

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A B S T R A C T

A novel method is presented for the visualisation of steady-state concentrations and exposures that may result from the indoor release of hazardous airborne material. This impact matrix approach is designed for the analysis of air flow results for multizone building models and is intended to complement existing multizone software. The matrices are derived from a state-space formulation and can be used to directly calculate steady-state concentrations for continuous constant release rates, or exposures for finite mass releases. In addition to steady-state conditions, methods to visualise the time dependence of concentration and exposure are also provided. Example matrices are calculated and visualised for a single residential dwelling, an apartment block and a commercial healthcare building. The resulting impact matrices are interpreted to derive system level information on the spread of airborne material within the buildings. The results show important differences between the buildings that depend on their connectivity and ventilation.

1. Introduction

1.1. Motivation

Building simulation is a key tool in assessing the impact of hazardous airborne releases within buildings. In some cases the location and characteristics of airborne contaminant sources are well known in advance, but in others, such as deliberate terrorist attack or accidental release, there may be a wide range of possible source locations and different time profiles of the mass released. Traditional approaches for studying such releases involve the simulation of a small set of scenarios and the resulting analysis can be limited in scope. This work aims to provide a complementary method to evaluate the impacts from a wide range of release locations and to enhance the understanding of contaminant transport.

An alternative approach for the analysis of hazardous releases in whole buildings has been developed for use with multizone models. The method considers internal dispersion under steady flow conditions and uses a visual representation of the normalised steady-state concentrations for all potential release locations within the building. It can also be shown that the same quantities relate to the maximum integrated concentrations, or exposures, for finite duration releases of a given mass. These quantities can be used to understand the impact of indoor airborne releases on air quality as well as directly relating them to human health effects. As an additional benefit, the method provides a system level perspective on the building and its ventilation that may have a much wider application.

1.2. Background

Multizone models such as CONTAM [1] and COMIS [2] are a class of building simulation tools that predict air flows and concentrations of airborne contaminants throughout multiple zones within a building. Multizone models cannot provide detailed predictions of air flows within rooms that are available from computational fluid dynamics (CFD) methods. However, they can make predictions of zone averaged concentrations and have the advantage that they can be applied to whole buildings because of their moderate execution times. In addition, they do not require the high level of specific information on geometry and boundary conditions required by CFD models. They have also been subject to a number of validation studies including [3,4] that have included comparison of air flow and contaminant concentrations. Multizone models provide considerable additional detail when compared to simple single zone indoor models that are used in some situations [5]. They have

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been applied to a wide range of studies including indoor air quality [6,7], environmental tobacco smoke [8,9], spread of infectious disease [10,11] and monitoring and detection [12–14]. The numerical solution of contaminant transport within multizone models has also developed recently with the inclusion of additional solver options [15]. A useful overview of multizone and other indoor modelling methods can be found in Refs. [16,17].

Multizone models can be used to simulate single scenarios or a range of cases in turn. The results of these calculations are typically presented as time series plots of concentration for a given scenario or sometimes using coloured floor plans showing the spatial distribution of concentrations at a given time, or for a series of times [18]. However, a method to visually compare a range of release locations is not readily available. This paper sets out new methods for the visualisation of the resulting concentrations and exposures for multiple release locations and release profiles simultaneously. The use of integral solutions allows exposure to be assessed and compared for different locations without the explicit solution of concentration time series for specific release profiles. The method is not intended to replace CONTAM or the CONTAM results viewer, but aims to complement them by providing a concise, information-rich format to assist analysis and provide insight.

The methods take advantage of a state-space approach. State-space methods have become increasingly popular for building simulation studies. Yan et al. used these methods to model the emission of VOCs from building materials [19]. Wang et al. [20] applied state-space methods within a CFD framework to explore contaminant transport. State-space methods have also been used to study the control of temperature in three zones [21] and in multizone buildings [22], as well as for the detection of contaminant release events [23] and for studying the transport and dispersion of particles [24].

These previous studies demonstrate the flexibility and power of the approach. This work uses the formulation developed by Ref. [25] as a basis, because it allows the representation of many of the contaminant transport processes included within CONTAM. The same formulation has been extended and applied to the ingress of external contaminants in Ref. [26] and the solution of the resulting equations has been explored in Ref. [27]. The visualisation of contaminant transport using the state-space method was briefly introduced in Ref. [28], illustrating the potential for considering many release locations at the same time, a process which is not straightforward using other methods. This paper develops the theoretical basis for the visualisation methods and extends them, followed by demonstration of their use for three contrasting multizone building models.

2. Methodology

2.1. Theory

2.1.1. Assumptions

The multizone modelling approach [29,1] assumes that a building can be represented as a series of interconnected well-mixed zones. The analysis developed below also assumes that the air flow within the building is constant over the period of analysis. This assumption is consistent with the approach used within multizone models, which assume a quasi-static situation. This assumption may break down when the building is strongly influenced by meteorological conditions or for a mechanically ventilated building when there are sudden changes to the operation of the ventilation system. In such situations a series of steady states may be used.

2.1.2. Steady-state concentration

The change in internal concentration within a multizone building for a given air flow condition can be described by the state-space approach outlined in Refs. [25,26]. The governing equation for a multizone building with n zones can be written as

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \tag{1}$$

where $\mathbf{x} = [x_1 x_2 \ldots x_n]^{\mathrm{T}}$ and x_i is the concentration in zone i [kg m^{-3}]; $\mathbf{A}$ is the n-by-n state matrix [s^{-1}]; $\mathbf{B}$ is an n-by-n matrix accounting for the dilution of sources by the zone volumes [m^{-3}] and $\mathbf{u}$ is an n-by-1 vector describing contaminant inputs into the system [kg s^{-1}]. The state matrix describes the interactions between the zones due to air flow and also takes into account losses within zones and those due to transfer between zones. A full description of the state-space formulation can be found in Ref. [25].

When there is a continuous source of contaminants released at a constant rate, a steady-state concentration distribution, $\mathbf{x} = \mathbf{x}_{\mathrm{ss}}$, can be determined when $\dot{\mathbf{x}} = 0$. Substituting into (1) gives

$$\mathbf{x}_{\mathrm{ss}} = -\mathbf{A}^{-1}\mathbf{B}\mathbf{u}. \tag{2}$$

Where $\mathbf{x}_{\mathrm{ss}}$ is a column vector describing the steady-state concentration in each zone resulting from the release defined by the input vector $\mathbf{u}$.

The input vector can represent both external concentrations affecting the building and internal releases. For the purposes of this paper only internal sources are considered and $\mathbf{u} = \mathbf{u}_{\mathrm{int}}$. The internal source term vector, $\mathbf{u}_{\mathrm{int}}$, is defined as $\mathbf{u}_{\mathrm{int}} = [s_1 s_2 \ldots s_n]^{\mathrm{T}}$, where s_i is the source strength in zone i [kg s^{-1}].

If the case with a source in only one zone, j, is considered then $s_i = 0$ for $i \neq j$ and $s_i = r$ for $i = j$, where r is the release rate [kg s^{-1}]. For convenience we define a dimensionless n-by-1 source location vector, $\mathbf{u}_{\mathrm{dl}}(j)$, where $\mathbf{u}_{\mathrm{dl}}(j)_i = 0$ if $i \neq j$ and $\mathbf{u}_{\mathrm{dl}}(j)_i = 1$ if $i = j$. Therefore, $\mathbf{u}_{\mathrm{int}} = \mathbf{u}_{\mathrm{dl}}(j)r$ and by substituting into (2) the steady state concentration vector, $\mathbf{x}_{\mathrm{ss}}(j)$, for a release in a single zone, j, can be written as

$$\mathbf{x}_{\mathrm{ss}}(j) = -\mathbf{A}^{-1}\mathbf{B}\mathbf{u}_{\mathrm{dl}}(j)r. \tag{3}$$

It is straightforward to calculate the steady-state concentration from a release in each zone in turn by appending column vectors of $\mathbf{u}_{\mathrm{dl}}(j)$, where $j = 1..n$ to give

$$\mathrm{X}_{ss} = -\mathbf{A}^{-1}\mathbf{B}\mathbf{U}_{dl}r, \tag{4}$$

where $\mathbf{X}_{\mathrm{ss}}$ is an n-by-n matrix and $X_{ssi,j}$ is the steady state concentration in zone i resulting from a continuous release of strength r in zone j and

$$\mathbf{U}_{\mathrm{dl}} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix}. \tag{5}$$

It is clear that $\mathbf{U}_{\mathrm{dl}}$ is simply the identity matrix and therefore

$$\mathbf{X}_{\mathrm{ss}} = -\mathbf{A}^{-1}\mathbf{B}r. \tag{6}$$

We define the impact matrix $\mathbf{M} = r^{-1}\mathbf{X}_{\mathrm{ss}}$ by dividing the concentration matrix by the release rate and note that $\mathbf{M}$ has units of [m^{-3} s]. The impact matrix can then be calculated as

$$\mathbf{M} = -\mathbf{A}^{-1}\mathbf{B}. \tag{7}$$

The impact matrix, $\mathbf{M}$, summarises the distribution of normalised steady-state concentrations resulting from a continuous