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Impacts of contaminant storage on indoor air quality: Model development

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HIGHLIGHTS

- ► A lumped parameter model is applied to describe emission and storage buffering of contaminants.
- ► Model is used to assess impact of ventilation on indoor formaldehyde exposure.
- ► Observations of depletion of stored contaminants can be described by model.

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ABSTRACT

A first-order, lumped capacitance model is used to describe the buffering of airborne chemical species by building materials and furnishings in the indoor environment. The model is applied to describe the interaction between formaldehyde in building materials and the concentration of the species in the indoor air. Storage buffering can decrease the effect of ventilation on the indoor concentration, compared to the inverse dependence of indoor concentration on the air exchange rate that is consistent with a constant emission rate source. If the exposure time of an occupant is long relative to the timescale of depletion of the compound from the storage medium, however, the total exposure will depend inversely on the air exchange rate. This lumped capacitance model is also applied to moisture buffering in the indoor environment, which occurs over much shorter depletion timescales of the order of days. This model provides a framework to interpret the impact of storage buffering on time-varying concentrations of chemical species and resulting occupant exposure. Pseudo-steady-state behavior is validated using field measurements. Model behavior over longer times is consistent with formaldehyde and moisture concentration measurements in previous studies.

1. Introduction

In determining the concentration of indoor contaminants over time, interaction between the building materials and the concentration of the compounds in the air is often neglected. The time history of the airborne concentrations can be significantly different if such storage is present. This buffering of indoor concentrations resulting from storage can affect occupant exposure to these species, and can influence the effectiveness of various mitigation methods. Doubling the air change rate, for example, is often assumed to halve the steady-state concentration of a contaminant, but that may not be so if there is storage of that contaminant.

Here we discuss how a simplified model can describe the interactions between building materials and chemical species. While the term 'source' is often used to describe emitting building materials and furnishings, the term 'storage materials' is used here because materials initially uncharged with a contaminant can become loaded over time through interaction with the indoor air. Simplifying assumptions lead to a model that can be used to interpret storage buffering behavior in cases where properties of the storage materials are not well characterized. We will explore how this lumped parameter model behaves for formaldehyde and moisture. Similar models have been applied previously to describe the effects of storage on indoor concentrations of specific compounds (Dunn, 1987; Cummings and Kamel, 1988; Emmerich et al., 2002). This study presents the general form of the model, interpretation of the relevant parameters and timescales, and application to cases of interest. We also use the model to assess the impact of storage on long-term exposure to chemical species.

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Nomenclature

A	air exchange rate (h^{-1})
C	concentration in indoor air ($\mu g\ m^{-3}$)
C_{EL}	concentration in equilibrium layer ($\mu g\ m^{-3}$)
C_{eq}	initial concentration in equilibrium layer ($\mu g\ m^{-3}$)
C_∞	indoor concentration in absence of storage ($\mu g\ m^{-3}$)
$C_{material}$	concentration in storage material ($\mu g\ m^{-3}$)
C_{out}	outdoor concentration ($\mu g\ m^{-3}$)
C_{ss}	steady-state concentration ($\mu g\ m^{-3}$)
C_0	initial indoor concentration ($\mu g\ m^{-3}$)
ΔC	indoor minus outdoor concentration ($\mu g\ m^{-3}$)
ER	emission rate ($\mu g\ m^{-3}\ h^{-1}$)
k	transport coefficient ($m\ h^{-1}$)
kL	time constant for coupling between air and equilibrium layer (h^{-1})
L	loading factor = ratio of exposed storage material area to V (m^{-1})
S	storage-independent, internal sources plus AC_{out} ($\mu g\ m^{-3}\ h^{-1}$)
t	time (h)
V	volume of inside air (m^3)
$V_{material}$	volume of storage material (m^3)
Λ	rate constant for storage to come to equilibrium (h^{-1})
α	storage capacity of compound, equal to $\kappa V_{material}/V$ (−)
κ	affinity of the compound for the storage material (−)
τ_∞	storage depletion timescale (h)
τ_{ss}	repartitioning timescale (h)

2. Background

Chemical storage in building materials and furnishings has different implications depending on the species of concern. For moisture, one question of interest is to what extent does storage media buffer the humidity levels experienced in the space? For organic compounds, the concern is often how can exposure to such compounds be minimized? As a result, different strategies have been employed to describe the interaction between airborne species and storage media.

Concerns regarding formaldehyde emissions from pressed wood building materials led to attempts to quantify the emission rate from specific products (Myers, 1984). Although most exposure mitigation strategies continue to assume constant emission rates for indoor air contaminants such as formaldehyde, it has been established that the emission rate of formaldehyde depends on the indoor concentration and thus on the air exchange rate. Equivalent models (Fujii et al., 1973; Berge et al., 1980; Hoetjer and Koerts, 1986) assume that a thin air layer at C_{EL} is in equilibrium with the storage medium concentration $C_{material}$ at all times, $C_{EL} = f(C_{material})$, and that the emission rate per unit volume of the space, ER, is given by:

$$ER = kL(C - C_{EL}) \tag{1}$$

where C is the bulk air concentration and kL [s^{-1}] is the coupling time constant for the air and storage medium. The quantity kL is the product of a transport coefficient k and the loading factor L [$m^2\ m^{-3}$] which is the ratio of exposed storage material area to the room volume. The parameter kL can be interpreted as a time constant for the coupling between the near surface layer and the storage material. Although not all surfaces may initially contain and emit a chemical species, it is likely that over the initial period of repartitioning, additional surface materials will absorb and then re-emit the chemical as surfaces come to equilibrium with the airborne concentration.

This transport process can perhaps be described more accurately as two resistive processes in series (Sparks et al., 1996). The first barrier is between the bulk storage material and the interfacial zone and the second barrier between the interfacial zone and the bulk air concentration. In modeling emission of volatile organic compounds (VOCs) for example from synthetic stain on cabinetry or flooring, resistance between the interfacial zone and the room air tends to dominate. In the upper limit, k is proportional to the surface heat transfer coefficient and has a maximum value of 0.5–3 m h^{-1} (Sparks et al., 1996). In practice, however, there is often a surface coating layer which adds additional resistance between the storage material and the air. This resistance decreases the effective value of k. Such coatings can reduce k to 1/30th of value for the uncoated product, which helps to explain the range of k between 0.01 and 3.3 m h^{-1} reported in product emission tests (Myers, 1984).

The sorption of airborne chemical species onto solid material has been studied in great detail. Axley (1994) recommends that when a chemical species concentration in the storage medium is an order of magnitude less than the saturation concentration, it is appropriate to use the Langmuir isotherm or the linear isotherm model to relate the concentration of the sorbed material to that of the equilibrium layer. To model indoor air contaminants, it is common to use the linear isotherm model, which assumes the concentration at the surface of the storage medium is linearly proportional to the concentration in the equilibrium air layer:

$$C_{material} = \kappa C_{EL} \tag{2}$$

where κ is the affinity of the chemical species for the storage material.

Applying conservation of mass, the evolution of the indoor air concentration is governed by:

$$S - \dot{C} - A(C) = kL(C - C_{material}/\kappa) \tag{3}$$

where S is the amount of the compound injected into the space due to non-storage sources and outdoor air, and A is the dilution rate. It is clear that the indoor air concentration depends on the charge on the storage materials. Accordingly, if the storage material concentration changes significantly over time, the indoor air concentration will change as well.

Due to health concerns regarding chronic exposure to formaldehyde and other volatile organic compounds, there is interest not only in the indoor concentrations of such species but also how concentrations vary over time. It is difficult to quantify the timescale associated with depletion of formaldehyde sources in observational studies because this timescale tends to be long (a year or longer). Additionally, temperature and humidity can cause indoor concentrations to vary seasonally by up to a factor of two (Dingle and Franklin, 2002). Comparing single measurements in different homes, Hun et al. (2010) reported no correlation between house age and indoor air concentration of formaldehyde.

Limited studies have looked at how indoor formaldehyde concentrations vary in the same home over time. Sampling in nearly 300 homes in three subsequent summers, Park and Ikeda (2006) observed a decrease in indoor formaldehyde concentration in homes initially less than 6 months old. Dingle and Franklin (2002) reported the concentration tends to decrease if the home is less than 10 years old. Gilbert et al. (2008) reported higher indoor