A MUILTI-ZONE VENTILATION MODEL WITH CONTAMINANT EMISSIONS FROM BUILDING MATERIALS

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ABSTRACT

Source/sink models of volatile organic compound (VOC) emissions from building materials are reviewed and a multi-zone ventilation model is developed to predict concentrations of contaminants in rooms. The source model based on the principles of mass transfer and fluid flow presented by Zhang et al. (1995, 1996) is integrated into the multi-zone ventilation model. The characteristics of the parameters related to VOC concentration, i.e. Schmidt number, ventilation rate and air velocity at the free stream are investigated by the sensitivity analysis. As a result of the simulation, VOC concentration is decreased as the ventilation rate is increased, and the concentration is decreased as the Schmidt number is increased. However, the air velocity does not affect the concentration if the velocity is not low. In addition, a numerical example of multi-zone ventilation model is presented.

KEYWORDS

Indoor air quality, Multi-zone ventilation, Source/sink model, Computer simulation

INTRODUCTION

In recent years, poor indoor air quality caused by air-tightness, volatile organic compounds (VOCs) from materials and insufficient ventilation rate in buildings have lead to building related illness, i.e. Sick Building Syndrome (SBS) or chemical hypersensitivity, which should not be ignored. Indoor air quality (IAQ) models are recognized to be very important to understand how the factors that affect indoor air quality related to each other and to predict concentrations of contaminants for places and conditions that cannot be measured (Maroni et al. 1995). The model can also be used for risk assessment to evaluate human health. Various studies related to material emissions and IAQ modeling have been developed to predict and evaluate IAQ in rooms. Few researches on IAQ modeling integrated with material emissions have been presented. The source/sink models of VOC emissions from building materials are reviewed and a multi-zone ventilation model is developed to predict VOC concentrations in rooms.

SOURCE/SINK MODELS

In general, mathematical IAQ models to describe the material emission process can be categorized into two groups, empirical (experimental) models and physical models. The empirical models are based on fitting an appropriate mathematical expression to a set of experimental data. Small test chambers have been used to develop the model. The concentration versus time data is used to determine the parameters of empirical source models. The first-order decay model is expressed by an exponential function for the source term (Chang et al. 1993, Clausen et al. 1993), and a double exponential decay model has been developed to describe the physical process precisely (Colombo et al. 1992, Guo 1993). The empirical models do not provide a physical description of the emission process, nor do they separate the parameters describing the source from those describing the environment (Tichenor et al.1993).

Physical models are based on fundamental mass transfer processes. Guo and Tichenor (1992) developed the model based on Fick's Law of Diffusion. A compartment model developed by Christiansson et al. (1993) is essentially an approximate numerical technique based on the integrated finite difference method for solving parabolic partial difference equations such as the diffusion equation. Evans (1996) also presented the compartment model and described a linear systems analysis to solve the model. Levsen et al. (1993) presented a model divided the total test system into four compartments, source, gas phase, sinks and exit. Zhang and Haghighat (1995,1996) developed a mathematical model based on both mass diffusion and mass convection processes in the boundary layer between the material surface and the airflow. The model does not require any experimental data as input.

On the other hand, experimental and theoretical researches on sorption process have been developed. The theoretical bases of sorption models were developed by Axley (1993). Bortli et al. (1996) presented a new mathematical model with two compartments ("two-sink model").

A MULTI-ZONE IAQ MODEL

A multi-zone IAQ model can be generalized to predict the concentration of a compound, emitting from a source in a room, adsorbing to and desorbing from material surfaces in the room. The equation of mass balance for each zone can be expressed as

$$V_i \frac{\partial C_i}{\partial t} = \sum_{j=1}^{N_j} Q_{j,i} C_j - \sum_{i=1}^{N_i} Q_{i,j} C_i + S_i + R_i \quad (1)$$

where C_i is the concentration of the pollutant in zone i (mg/m^3), V_i is the zone volume (m^3), $Q_{i,j}$ denotes the ventilation rate from zone i to zone j (m^3/h), N_i is the number of openings in room i, S_i is the emission term from the material surfaces in zone i (mg/h), and R_i is the sink term related to adsorption and desorption in zone i (mg/h). If Langmuir adsorption processes are assumed, then the following equations are used to obtain R (Tichenor et al. 1990).

$$R = -Ak_aC + Ak_dM \quad (2)$$

$$\frac{dM}{dt} = k_aC - k_dM \quad (3)$$

where A is the sink area (m^2), k_a is the adsorption rate constant (m/h), k_d is the desorption rate constant (h^{-1}) and M is the mass per unit area on the sink (mg/m^2). The source model based on the principles of mass transfer and fluid flow developed by Zhang and Haghighat is used in this paper. The main advantage of the model is that the model does not require any experimental data as input. The mass emission rate can be expressed as

$$m = \frac{b\tau_0}{\rho U_\infty} S_c^{-\frac{2}{3}} \frac{C_\infty}{(r_1 - r_2)} [(r_1 + N)e^{r_1 t} - (r_2 + N)e^{r_2 t}] \quad (4)$$

$$m = \frac{b\tau_0}{\rho U_\infty} S_c^{-\frac{1}{2}} \frac{C_\infty}{(r_1 - r_2)} [(r_1 + N)e^{r_1 t} - (r_2 + N)e^{r_2 t}] \quad (5)$$

$$r_{1,2} = \{-(N + LH + HC_\infty / M_o) \pm [(N + LH + HC_\infty / M_o)^2 - 4NHC_\infty / M_o]^{\frac{1}{2}} / 2 \quad (6)$$

where S_c is the Schmidt number, ρ is the air density, τ_0 is the wall shear stress, b is a constant, C_∞ is the initial concentration of contaminant (mg/m^3), U_∞ is the boundary condition for air velocity at the free stream, N is the air exchange rate (h^{-1}), L is the product loading factor $=As/V$ (m^2/m^3), As is the source area, M_o is the initial mass (mg/m^2) and H is expressed as

$$H = b\tau\rho^{-1} U_\infty S_c^{-\frac{2}{3}} \quad (7)$$

Therefore source term S is given by $S=mAs$.

Multi-zone Flow Model Descriptions

The multi-zone flow model used in this paper is based on the ventilation network theory, and a module to predict the pollutant concentration in each zone is integrated into the main program. The ventilation rate Q for each opening can be obtained by solving this flow model, and then the concentration of contaminant in each zone is calculated using Equation (1). The general equations for the pressure difference at openings and the equation of continuity that the density of air is assumed the same in each zone are used. The explicit finite difference method is used for solving the equations.

Sensitivity Analysis

The parameters related to the material emission rate and the concentration of contaminant in Equations (1) to (7), i.e. Schmidt number, ventilation rate and air velocity at the free stream are investigated by computer simulation. A single zone model with two openings is used and no sink effect is assumed as shown in Figure 1 and Table 1. Figures 2 and 3 show the emission rate and the concentration of contaminant versus time according to air exchange rate respectively. The emission rate in the case of large air exchange rate is larger than the other cases in the early time, but the decay curve decreases more quickly as time passes. Therefore, the concentration changes largely according to air exchange rate. The peak of the concentration is large when the air exchange rate is small and the concentration decay is very slow.

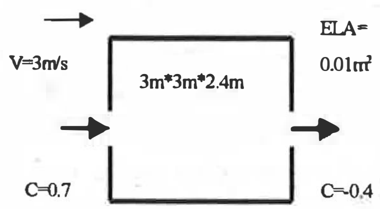

Figure 1 Single zone model

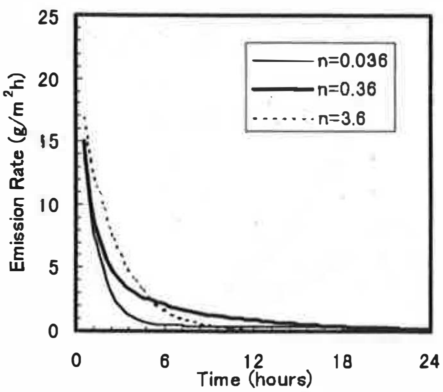

Figure 2 Emission rate versus time curves according to the different air exchange rates

Table 1 Calculation conditions

Dimensions:	3m*3m*2.4m
Source area:	9 m^2
Outdoor wind speed:	3m/s
Wind pressure coefficient:	0.7, -0.4
Equivalent Air Leakage:	0.001 m^2/opening
Air viscosity:	1.589 10^{-5} m^2/s
Initial concentration:	0.0217 kg/m^3
Initial mass:	0.05 kg

Figures 4 and 5 show the emission rate and the concentration versus time according to the Schmidt number respectively. The emission rate and the concentration in the case of low Schmidt number is larger than the other case except the early time. However, both of the values in the case of the Schmidt number 1.0 are larger than the other cases in the early time.

The emission rate and the concentration according to air velocity at the free stream are shown in Figures 6 and 7. Both of the values in the case of U=0.03 and 0.1m/s are almost similar, but in the case of low velocity the concentration is larger than the other cases except the early time.

The sink effect is investigated using the same single zone model as shown in Figure 1. The sink area is set at 9 m^2. The adsorption rate constant 0.257 m/h and the desorption rate constant 0.429 h^{-1} are used (Jorgensen et al.

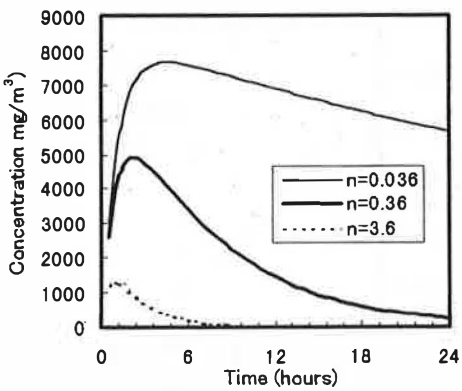

Figure 3 Concentration versus time curves according to the different air exchange rates

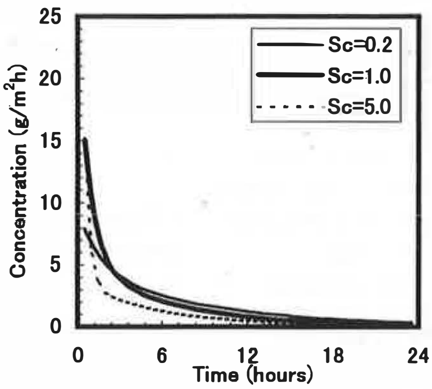

Figure 4 Emission rate versus time curves according to the different Schmidt numbers

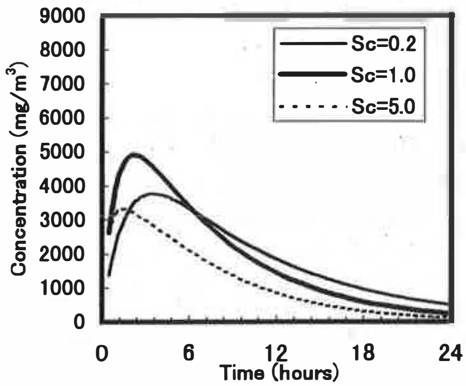

Figure 5 Concentration versus time curves according to the different Schmidt numbers

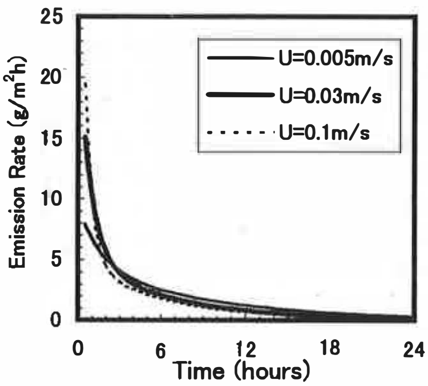

Figure 6 Emission rate versus time curves according to the air velocities at the free stream

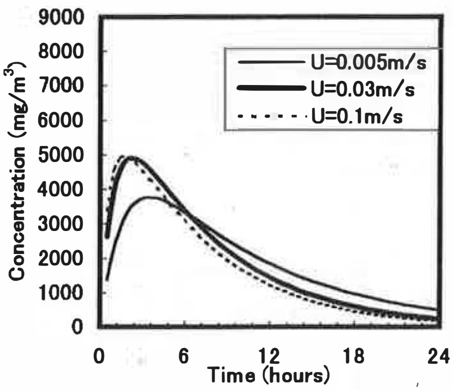

Figure 7 Concentartion versus time curves according to the different air velocities at the free stream

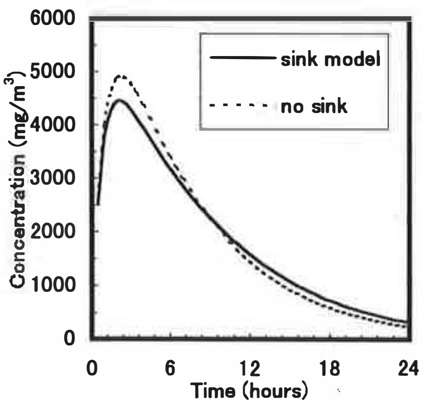

Figure 8 Comparison of concentration with/without sorption

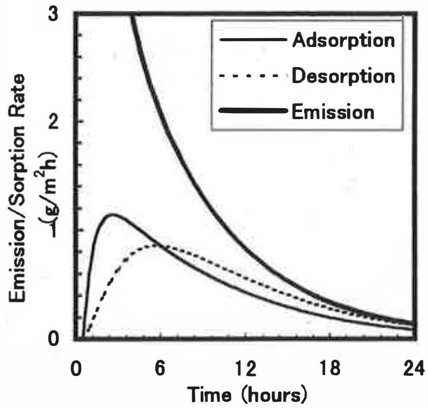

Figure 9 Emission and sorption rate versus time curves

1993). The difference between the source/sink model and the model without sorption is shown in Figure 8. The emission rate, the adsorption and the desorption rate are shown in Figure 9. The adsorption effect is appeared in the early time, and the desorption effect is also noticed after 6 hours.

MULTI-ZONE IAQ SIMULATION

A numerical example of two-zone IAQ model as shown in Figure 10 is presented. Two models with/without sorption in room 2 are investigated. The same physical properties excluding the Schmidt number 2.8 and the initial conditions as the previous single model are used.

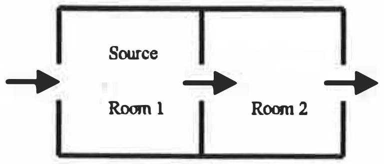

Figure 10 Two-zone model

Figure 11 shows the emission rate and the sorption rates for the two-zone IAQ model with sorption. The concentrations of contaminant in the two models are shown in Figure 12.

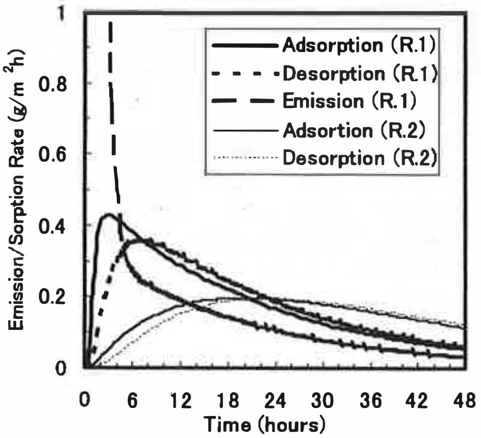

Figure 11 Sorption and emission rate versus time curves

CONCLUSIONS

A multi-zone IAQ model is developed to predict VOC concentrations in rooms. The source model based on the principles of mass transfer and fluid flow is integrated into the multi-zone ventilation model. The characteristics of the parameters related to VOC concentration, i.e. Schmidt number, ventilation rate and air velocity at the free stream are investigated by the sensitivity. As a result of the calculations, the VOC concentration in the room air is decreased as the ventilation rate is increased, and the concentration is increased as the Schmidt number is increased. However, the air velocity does not affect the concentration if the velocity is not low. The adsorption effect of the sink model is appeared in the early time, and the desorption effect is also noticed as time passes. In addition, a numerical simulation of two-zone ventilation model is presented.

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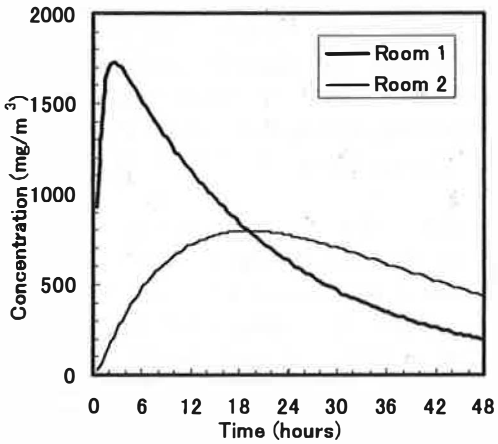

Figure 12 Concentration versus time curves

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