APPLICATION OF A WHOLE ROOM INDOOR AIR QUALITY (IAQ) MODEL

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ABSTRACT

In a previous study, a whole room IAQ model consisting of multi-phase emission/sorption model for wall materials and room volume mass balance model catering for practical ventilation schemes was developed. The interactions between volatile organic compounds (VOCs) and building materials composing different building components can thus be modeled based on fundamental mass transfer theories. In the present study, the effects of various ventilation strategies and outdoor source on the indoor gas phase VOC concentration are investigated by simulating different building scenarios. Results show that lead time provision of ventilation can significantly lower the peak indoor VOC concentration at the beginning of the occupancy and also the gas phase VOC concentration during the whole working day. Prolonging the provision of ventilation after the occupants have left seems not to improve the indoor air quality the next working day. The outdoor VOCs sources seem to have substantial effects on indoor VOCs concentration.

KEYWORDS

Building material, Emission, Sorption, Diffusion, Ventilation

INTRODUCTION

It has been scientifically found that VOCs have adverse health effects on people, which can be either acute or chronic; VOCs concentration in indoor air is usually higher than in outdoor air; people spend most of their time in indoor environment. Building materials are recognized to be a major source of indoor VOCs and some of the materials are known to act as sinks. All these facts have created the demand of a decision-making tool, which can be used not only to predict indoor VOCs concentration, but to evaluate and improve various indoor air quality control strategies.

The single-layer (Lttle et al., 1994), double layer model (Kumar and Little, 2003) and multi-layer model (Li and Niu, 2005) assume only one component existing in the 'room', thus the 'room' is more like an environmental chamber. In real buildings, the situation is more complex, there are different building components in a real room, such as the wall assemblies, the floor assembly and the ceiling assembly, and each component may be composed of different layers of porous or non-porous materials. (Zhang and Niu 2004) developed a multi-component continuum model to predict indoor VOCs emissions from building materials in a typical office room. However, there are two weakness in this model. First of alll, it assumed that all building materials are homogeneous, which is obviously unrealistic, and secondly, it did not take HVAC operation mode into consideration by simply assuming a constant air change rate.

Recently (Li and Niu 2007) developed a single-zone IAQ model consisting of a multi-phase emission and sorption model for multi-layer floor, ceiling and wall materials. The model is novel in that it assembles most of the components that may potentially affect gas-phase VOC concentrations of a reasonably realistic room in a building. Therefor, the impact of dynamic VOC emission/sorption processes on the effectiveness of a certain ventilation scheme, or the influence of a certain ventilation scheme on the emission behavior of indoor building materials can be extensively investigated. This paper futher explored the applications of the novel model.

HINTS OF THE MODEL

A variety of building materials may exist in the room, some of them may be porous materials, and others may be less porous materials which sometimes can be regarded as non-porous materials for the sake of simplicity. The mass transfer mechanisms for VOCs in the porous and non-porous materials are significantly different. For non-porous materials, material phase VOCs diffusion, surface partitioning (equilibrium between material phase surface concentration and gas phase concentration in the boundary), and surface convection are the major processes involved, while for porous materials, gas phase VOCs diffusion (surface diffusion and adsorbed phase diffusion can normally be neglected), sorption on pore surfaces (equilibrium between gas phase VOCs concentration and adsorbed phase VOCs concentration), and surface convection are the three main processes.

Although the corresponding forms of governing equations, boundary conditions and initial conditions, as well as the variables in the equations may be different for non-porous and porous materials; a universal form can be written and thus the model is solvable. Due to the limited space available, the details of the model, which can be found in "Control of volatile organic compounds indoors – Development of an integrated mass-transfer-based model and its application" (Li and Niu, 2007), are omitted here.

DESCRIPTION OF THE MODELED ROOM

The model room is a 3×3×3 m^3 small office room. Assume one occupant occupies this room. The room was mechanically air-conditioned by a constant volume system delivering supply air at the rate of 18 L/s, and the fresh outdoor airflow rate was 7.5 L/s. The infiltration airflow rate was kept at 0.75 L/s, which was equivalent to an infiltration air change rate of 0.1 h^{-1}.

The in-duct filter was in effect when the HVAC system was working, since gaseous air cleaning device's efficiency data is less widely available than that for particle filters, due in part to the lack of a standardized test method for determining these efficiencies, in this paper its efficiency was assumed to be 35% according to limited test data done by several other researchers.

For intermittent ventilation, the HVAC system was assumed to work from 8:00 AM to 8:00 PM during the work-hours and to shut off during off-work hours and weekends.

The building interior materials are show in *Figure 1*. The structures of the construction are as follows: the sidewalls are composed of three layers, 240 mm brick, 5 mm concrete, and 0.2 mm wallpaper, counting from the outermost layer to the innermost layer; the ceiling is composed of two layers, 200mm concrete and 10mm gypsum board, counting from the uppermost layer to the bottommost layer; the floor is composed of three layers, 200 mm concrete, 10 mm gypsum board, and 15 mm carpet, counting from uppermost layer to bottommost layer.

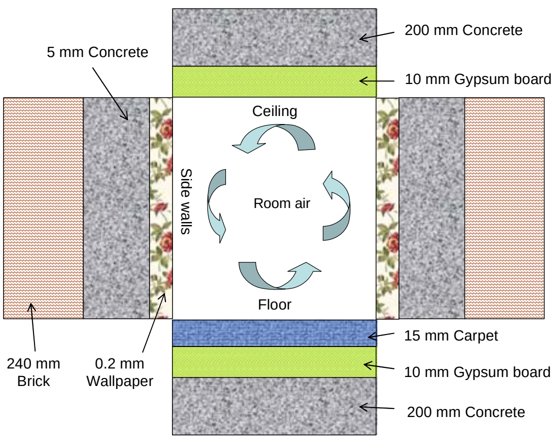


Figure 1 Structures of sidewalls, ceiling and floor

MODEL PARAMETERS

The physical properties of the materials shown in *Figure 1* are summarized in *Table 1*. The modeled compound is selected as Ethyl acetate, because this compound is commonly encountered indoors and whose boiling point is relatively low, which means its vapor is readily inhaled by occupants. The chemical and physical properties of Ethyl acetate are listed in *Table 2*. The emission parameters for the selected VOC/material combinations are presented in *Table 3*.

Table 1 Densities and porosities of materials

MATERIAL	DENSITY ($KG\ M^{-3}$)	POROSITY (%)
Wallpaper with paste	1300	10
Carpet with SBR backing	295.29	15
Solid concrete	2298	10.4
Brick wall	1680	17.1
Gypsum board	774.4	28

Table 2 Chemical and physical properties of Ethyl acetate

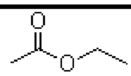
VOCS PROPERTIES	ETHYL ACETATE
Molecular Structure	
Molecular formula	$CH_3COOC_2H_5$
Molecular weight (g mol^{-1})	88.1
Boiling point (°C)	77.5-77.5
Polarity (10^{-24} m^3)	9.7
CAS number	141-78-6

Table 3 Emission parameters of VOC/materials

MATERIAL	EFFECTIVE DIFFUSIVITY ($M^2\ S^{-1}$)	SORPTION COEFFICIENT (M^3 AIR/M^3 MATERIAL)
Wallpaper with paste	8.33×10^{-9}	3000
Carpet with SBR backing	4.52×10^{-7}	42.2
Solid concrete	5.06×10^{-8}	1140.69
Brick wall	4.74×10^{-7}	182.33
Gypsum board	1.13×10^{-6}	86.65

Table 4 Simulated cases

	HVAC SYSTEM ON	HVAC SYSTEM OFF	OUTDOOR SOURCE
Strategy A*	8:00-20:00	20:00-8:00	-
Strategy B	6:00-20:00	20:00-6:00	-
Strategy C	8:00-22:00	22:00-8:00	-
Strategy D	8:00-20:00	20:00-8:00	Sinusoidal

*Reference case

The carpet in the room was assumed to be the VOC source, and its initial gas-phase VOC concentration was $C_{6,1}(x_{6,1},t)\big|_{t=0} = 236.97$ mg m^{-3}. The initial indoor VOC concentration was assumed to be zero.

The current simulation lasts for one week, starting from 0:00 Monday to 24:00 Sunday.

Several different cases are investigated in this paper as listed in *Table 4*.

RESULTS AND DISCUSSION

Emission behaviors of different building components

It is known that the emission rate or emission factor of VOCs from building material firstly increases to a peak and then decays continuously when constant flowrate of outdoor air is provided. How the behavior of emission factor would change with the circulation of on/off scheme of HVAC system is an interesting question. Since the behaviors of emission factors for different intermittent ventilation strategies are similar, for instance, emission factors from sidewalls, ceiling and floor for the Reference case (strategy A) are computed. The results are presented in *Figure 2*. It can be seen that all the indoor surfaces present sudden increases in emission factor at the starting-up of the air conditioning system in the early morning. This may be caused by the sudden provision of ventilation - consequently relatively large convective mass transfer coefficient is resulted. Opposite phenomenon (i.e. sudden decrease) is observed when the HVAC system is switched from the state 'on' to 'off'.

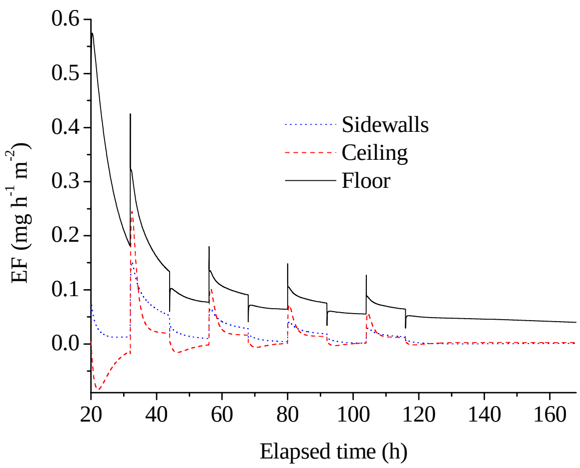


Figure 2 Behaviors of emission factors from different building components under the Reference case

It can also be found that most of the indoor surfaces become VOCs sources after the starting-up of the HVAC system, and some of the sorptive components (e.g. the ceiling) may re-adsorb VOCs during the HVAC shut-off period. This sink effect may have adverse effect on indoor air quality. Although it will lower the peak indoor concentration, it will also prolong the presence of VOCs in indoor environment. So, proper selection of interior building materials is of vital importance to good indoor air quality. Actually, the interactions between the indoor air and the indoor surfaces are very complicated. The operation of the building, the pollutant sources and the physical and chemical processes affecting the pollutants all affect the efficacy of ventilation for controlling VOCs concentrations. So source control measures, in addition to adequate ventilation, are required to limit concentrations of VOCs in indoor environment (Hodgson et al., 2003).

Lead-time provision of ventilation

It is also known that elevated VOCs concentration is likely to be encountered in the early morning due to the absence of ventilation during the past night in case intermittent ventilation is employed. The extent of contaminant buildup depends on the source strength, sorption capacity of indoor building materials, the infiltration rate and also the environmental conditions. The VOCs concentration is likely to be at a substantially elevated level before occupancy begins in the next morning. This would yield higher dynamic and mean exposures for the employees, which may affect their productivity and health as well.

A morning pre-occupancy flush-out may be helpful in lessening this phenomenon. Therefore, it is necessary for the HVAC system to operate before occupancy begins in the morning. *Figure 3* shows the concentration curves resulted from ventilation strategies A and B, respectively.

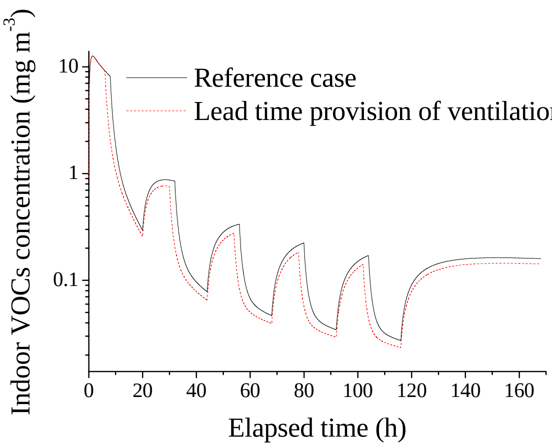


Figure 3 Impact of lead-time provision of ventilation on indoor VOCs concentration

It can be seen that a 2 h lead-time provision of ventilation does significantly reduce the peak concentration at the time occupancy begins and the concentration in the working day. Practically speaking, maximizing the outdoor air flow rate during this period would achieve even better indoor air quality if leaving energy consumption out of account. Anyway, there should be a balance between maintaining good indoor air quality and low energy consumption.

Prolonging provision of ventilation

It is also worthwhile investigating the effect of prolonging provision of ventilation (strategy C) on the next day's indoor pollution level. The simulation results presented in ***Figure 4*** show that this strategy seems to have little potential for the improvement of the air quality the next work day. However, if the majority of the employees work overtime, this practice should be implemented to make sure that there is sufficient fresh air provision and also to maintain good indoor air quality. While if there is only several employees (e.g. one or two) stay longer (e.g. one or two hours) after the working hours, the HVAC system could be shut off after normal working hours to save energy because the simulation results show that the indoor contaminant concentration will not increase too much for this kind of situation. (J rgensen 2007) also drew a similar conclusion through investigating the sorption of VOCs on material surfaces under intermittent ventilation in an environmental chamber.

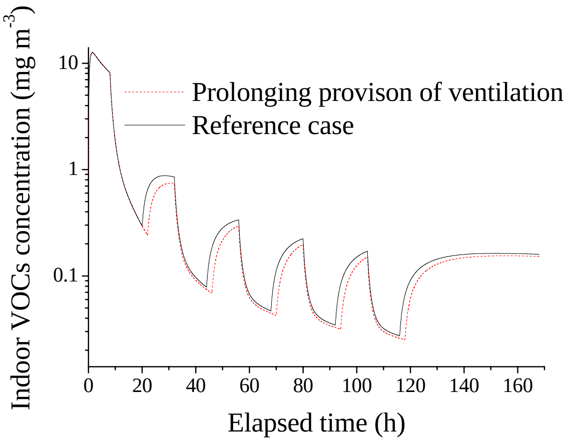


Figure 4 Impact of prolonging provision of ventilation on indoor VOCs concentration

Outdoor VOC source

Quite often, the modelers assume that the outdoor air is free of VOCs, partly due to the insufficient information in this regard. In order to evaluate the impact of this assumption on indoor gas phase VOCs concentration, a sinusoidal outdoor VOC source concentration profile (Strategy D) is assumed. The source function is described by a sinusoidal function,

$$C_{OA}(t) = 0.04\sin\left(\frac{2\pi}{24}t\right) + 0.08$$

where C_{OA} is in mg m^{-3} and t in hours. Practical examples of this type of source include atmospheric contaminants from motor vehicle exhaust, and concentration patterns of toxic organic pollutants such as benzene in outdoor air in Los Angeles (Zhao et al., 2002).

Figure 5 shows the simulated results of considering and neglecting the sinusoidal source, respectively. It should be pointed that neglecting the outdoor VOCs sources may lead to dramatically underestimated indoor VOCs concentration, which is risky for accurate exposure estimation and proper implementation of VOC control strategies. This reminds our modelers that any assumptions made should be validated before the model can practically be used.

Regarding the outdoor VOCs sources, it is recommended that periodical monitoring and recording be implemented whenever condition allows, in particular where strong sources exist, e.g. near car park, restaurant, and road etc. The history of the outdoor VOCs source concentration can be a good reference for modeling input if the surroundings are almost unchanged.

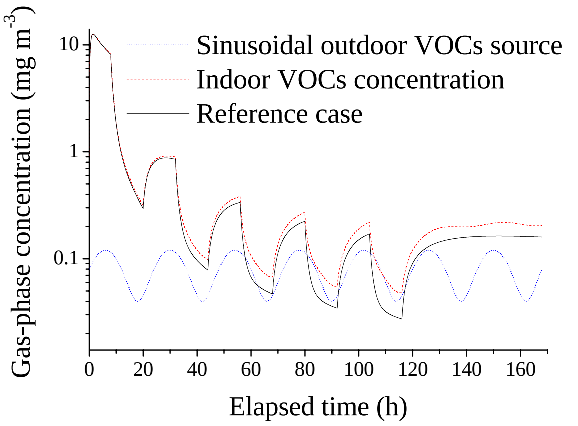


Figure 5 Impact of outdoor VOCs sources on indoor VOCs concentration

CONCLUSION

In this paper, a previously developed whole-room IAQ model is used to study the emission behaviors of different building components, to evaluate several different ventilation schemes, and to investigate the impact of outdoor souce on indoor gas phase concentration.

It is found that some of the sorptive components can act as sinks during the period of no ventilation provided, while they can also act as sources during the period of sufficient ventilation provided. Proper selection of indoor building materials is thus suggested.

Lead-time provision of ventilation seems to be a good practice to significantly lower the indoor contaminant peak concentration at the commencement of occupancy and to substantially improve the indoor air quality during the working hours.

Prolonging provision of ventilation after normal working hours seems not to improve the indoor air quality the next working day. This practice could be used only if the majority of the employees work overtime, otherwise it is a waste of energy.

The outdoor VOCs source concentration may have great impact on the indoor VOCs concentration. The assumption of zero outdoor VOCs concentration usually made in IAQ model may result in underestimated indoor concentration.

The model has proven to be able to deal with different real building scenarios. It is likely to be a simple routine tool for building owners, designers and operators to attain acceptable indoor VOC concentration level.

ACKNOWLEDGMENT

This research was financially supported by the Hong Kong RGC CERG Grant PolyU5129/03E.

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