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A Pre-assessment and Control Tool for Indoor Air Quality (PACT-IAQ) Simulation in Actual Buildings

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Abstract

This study introduced a pre-assessment and control tool for indoor air quality (PACT-IAQ) which aimed at multiple pollutant concentrations simulations, pollutant loads estimations and decoration design scheme optimization. Multiple emission sources, sinks, ventilation, pollutant dissemination, and the combined effects of temperature and humidity on material emissions were considered in the tool. Two versions, namely the single zone and multi-zone models, were included in the tool. Emission database of building material was developed to ensure the engineering application of this simulation tool. The simulation tool was applied to an office building and field measurements were performed after the completion of building construction. Comparison results between simulation and measurement data showed the acceptable accuracy of it. The PACT-IAQ has promising application in indoor pollutant control.

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Keywords: volatile organic compounds; mass transfer model; pollutant loads; combined effects of temperature and humidity; engineering application

1. Introduction

Indoor air quality (IAQ) plays a significant role to human health. There are massive pollutants have been identified and proved to be harmful. Pollutant concentrations and their variations are significant to help coming up with effective control strategies.

The most commonly used control strategies for IAQ are emission source control, ventilation and air cleaning. However, those control strategies are mainly post-processing methods which focus on the stage after the completion of building construction. The pre-assessment method aimed at improving IAQ at the design stage is another alternative. IAQ pre-assessment and control is mainly achieved by IAQ simulations. However, even there are a series of IAQ simulation programs have been developed, such as RISK [1], MCCEM [2], MEDB-IAQ [3], CHAMPS [4] and ACCESS-IAQ [5], their engineering applications in actual buildings are rather rare due to the limitation of the empirical emission source/sink models, the lack of emission database or the over-simplify and insufficient consideration of the influencing factors.

This study first analysed the main influencing factors on IAQ. Then the basic framework, the theoretical models of the pre-assessment and control tool for IAQ (PACT-IAQ) were introduced. The accuracy of the simulation results of PACT-IAQ was verified by an engineering project.

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Nomenclature	
A_s	the area of the sorption material s , m^2
A_n	the emission area of material n , m^2
$C_a(t)$	the VOC concentration, mg/m^3
$C_{ai}(t)$	the VOC concentrations of zone i , mg/m^3
$C_{aj}(t)$	the VOC concentrations of zone j , mg/m^3
$C_{out}(t)$	the outdoor VOC concentrations, mg/m^3
$CADR$	the clean air delivery rate of air cleaners, m^3/h
$E_n(t)$	the emission rate from material n , $mg/(m^2 \cdot h)$
N_{Ei}	the total number of the emission sources in zone i
N_{Si}	the total number of the sinks in zone i
$Q_{j-i}(t)$	the ventilation rates from zone j to zone i , m^3/h
$Q_{i-j}(t)$	the ventilation rates from zone i to zone j , m^3/h
$Q_{out_ini}(t)$	the ventilation rate from zone i to outdoor, m^3/h
$Q_{out}(t)$	the ventilation rate from outdoor to indoor, m^3/h
$R_s(t)$	the sorption rate of sorption material s , $mg/(m^2 \cdot h)$
t	time, h
V	the volume of aimed building, m^3
V_i	the volume of zone i , m^3

2. Method

2.1. Influencing factor analysis and their simplification

The PACT-IAQ is mainly focused on two different kinds of pollutants, namely volatile organic compounds (VOCs) and particulate matter. Take indoor VOCs as an example, the concentrations are influenced by many factors which are illustrated in Fig. 1. These factors can generally be divided to emission sources/sinks, ventilation and air cleaning.

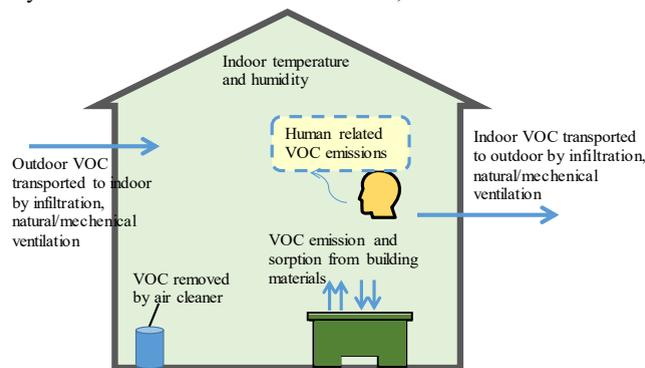


Fig. 1. The main influencing factors of indoor VOC concentrations

Emission and sorption from different kinds of building materials influence the pollutant loads indoor, and then affect indoor VOC concentrations. However, not all kinds of building materials are main emission sources. Thus, the main emission sources selection is recommended to be conducted before IAQ simulation. This could be done in two ways. First, materials that were known as VOC emission sources from previous studies were directly chosen. Otherwise, qualitative or quantitative measurements using headspace measurement or a small-scale environmental chamber are needed to make the selection. Moreover, the time schedule of building construction and decoration influence the age of building materials from the emission to the simulation due time. This should also be considered in the tool [6].

Ventilation plays a role in the pollutant dissemination among rooms as well as the transport between indoor and outdoor. For mechanical ventilation, the supply air rate, fresh air rate, exhaust air rate of the simulated room need to be collected. For natural ventilation, ventilation rate is affected by outdoor environmental conditions, indoor temperature, air tightness and window/door opening behaviors of the buildings etc. Thus the natural ventilation rate will vary with time and very hard to be determined accurately. According to our sensitivity analysis, ventilation rate with all window/door closed is more important to indoor VOC concentration simulation than the occasion with window/door opened. Thus, ventilation rate with window/door closed is recommended to be measured directly or simulated by the ventilation software. Ventilation rate with window/door opened could either be simulated by the ventilation software or simplified to a constant value, e.g. 5 h^{-1} , for the single zone model sometimes

when the window/door are opened.

Air cleaning techniques are widely used indoors. Air cleaner is one of the most popular used approaches. The clean air delivery rate (CADR) was used to represent the air clean ability of it.

Environmental conditions such as temperature and humidity, wind speed and direction could also influence indoor VOCs from two different aspects. On the one hand, the environmental conditions influence the wind pressure of the buildings, which will influence the ventilation rate and pollutant disseminations. On the other hand, indoor temperature and humidity may affect material emissions and sorption rates. Thus, their effects are considered in the ventilation and material emission/sorption models in PACT-IAQ.

2.2. Framework of PACT-IAQ

Based on the influencing factor analysis, the framework of PACT-IAQ includes three main input modules, the emission source/sink, ventilation and air cleaning, and one output modules, which is illustrated in Fig. 2. Each input module includes several mathematical models.

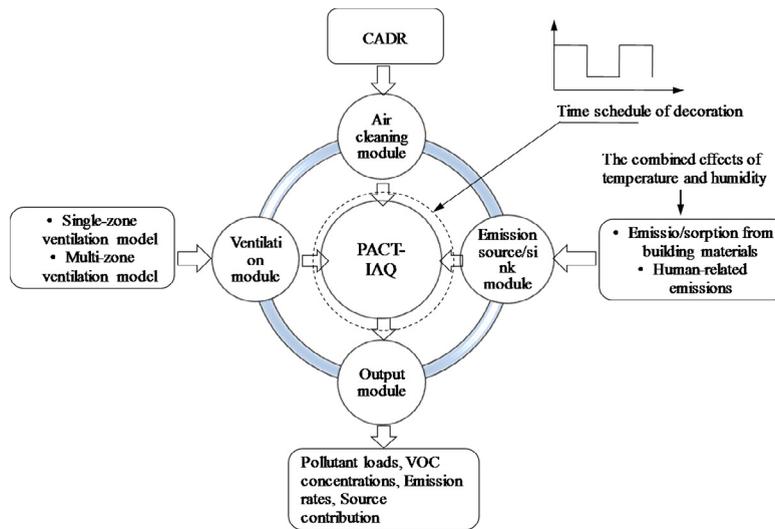


Fig. 2. The framework of PACT-IAQ

2.3. Mathematical models of PACT-IAQ

• Room models

The model assumes that the building is divided to multiple air zones and the air is well-mixed in each zone. The room model of the PACT-IAQ is based on the law of mass conservation. For chemical pollutants like VOCs, the mass balance equation of the multi-zone model can be expressed as:

$$V_i \frac{dC_{ai}(t)}{dt} = \sum_j Q_{j-i}(t)C_{aj}(t) - \sum_j Q_{i-j}(t)C_{ai}(t) + Q_{out_ini}(t)C_{out}(t) - Q_{in_outi}(t)C_{ai}(t) + \sum_{n=1}^{N_{Ei}} A_n E_n(t) - \sum_{s=1}^{N_{Si}} A_s R_s(t) - CADR * C_{ai}(t) \quad (1)$$

Where V_i is the volume of zone i , m^3 ; $C_{ai}(t)$ and $C_{aj}(t)$ are the VOC concentrations of zone i and zone j , mg/m^3 ; t is time, h ; $Q_{j-i}(t)$ and $Q_{i-j}(t)$ are the ventilation rates from zone j to zone i and zone i to zone j , respectively, m^3/h ; $Q_{out_ini}(t)$ is the ventilation rate from outdoor to zone i , m^3/h ; $Q_{in_outi}(t)$ is the ventilation rate from zone i to outdoor, m^3/h ; $C_{out}(t)$ is the outdoor VOC concentrations, mg/m^3 ; A_n is the emission area of material n , m^2 ; $E_n(t)$ is the emission rate from material n , $mg/(m^2 \cdot h)$; N_{Ei} is the total number of the emission sources in zone i ; A_s is the area of the sorption material s , m^2 ; $R_s(t)$ is the sorption rate of sorption material s , $mg/(m^2 \cdot h)$; N_{Si} is the total number of the sinks in zone i ; $CADR$ is the clean air delivery rate of air cleaners, m^3/h .

When the VOC concentrations between zones are well-mixed, then single zone model could be used and the mass balance equation could be expressed as:

$$V \frac{dC_a(t)}{dt} = Q_{out}(t)C_{out}(t) - Q_{out}(t)C_a(t) + \sum_{n=1}^{N_E} A_n E_n(t) - \sum_{s=1}^{N_S} A_s R_s(t) - CADR * C_a(t) \quad (2)$$

Where V is the volume of aimed building, m^3 ; $C_a(t)$ is the VOC concentration, mg/m^3 ; t is time, h; $Q_{out}(t)$ is the ventilation rate from outdoor to indoor, m^3/h ; $C_{out}(t)$ is the outdoor VOC concentrations, mg/m^3 .

- Ventilation models

According to the layout and mixing conditions of the simulated building, either single zone or multi-zone ventilation models could be used. When the zone number of the building is few or the air is well-mixed between zones, the single-zone model may be used. The building could be treated as one zone and ventilation rate of the zone should be given in the simulation. When the zone number is large, concentration differences may be occurred among zones, then multi-zone model is recommended. Ventilation between zones, between indoor and outdoor could be simulated by CONTAM.

- Emission/sorption models

To solve the above mass balance equations and obtain the time-varying indoor VOC concentrations, emission rates of different kinds of building materials should be estimated by different emission models. Generally speaking, building materials encountered indoor could be classified to dry material, wet material and composite material. Emission models used for different types of material in PACT-IAQ are listed in Table 1.

Table 1. Emission models used in PACT-IAQ

Material type	Emission model	References
Dry material	One-phase mass transfer model-without temperature and humidity effects	[7]
	One-phase mass transfer model-with temperature and humidity effects	[8]
	Double surface emission model	[9]
	Multi-layer emission model	[10]
Wet material	Exponential empirical models	[11]
	Numerical models	[12]
Composite material	Exponential empirical models	[11]
	Numerical model for composite material	[13]

Langmuir empirical model [14] is widely used for material sorption in existing IAQ software, such as RISK, MCCEM and IAQX. The sorption model [15] developed by Yang is used in ACCESS-IAQ. In PACT-IAQ, these sorption models as well as the model developed by Deng et al. [16] are also included.

2.4. Database development

Material emission database of PACT-IAQ is developed by small-scale and large-scale environmental chambers. Building materials were tested under constant environmental conditions, e.g. 25°C, 50%, $1h^{-1}$, over 72 h. Emission parameters were regressed by the grid searching method introduced by He et al. [17]. The database has been developed since 2009 and over 300 building materials were included in the database until now. The most widely used material types are included and it still under developing and more building materials will be added to it.

3. Engineering application and validation

To validate the accuracy of PACT-IAQ, formaldehyde concentrations of an office building were simulated and compared with the measurement data.

3.1. Basic information collection

The basic information need to be collected before IAQ simulation includes the layout of the building, the volumes of each rooms, the decoration material list, the area of building materials, decoration time schedule, and the indoor and outdoor environmental conditions. Fig. 3 is the layout of the office. Based upon the aforementioned methods, the main emission sources are selected and the corresponding areas are collected. Table 2 lists the room volumes and the areas of the building materials of the target rooms. Decoration time schedule and emission parameters of each material are listed in Tables 3 and 4, respectively. Ventilation rate of the office is simulated by CONTAM according to the layout and dynamic outdoor environmental conditions.

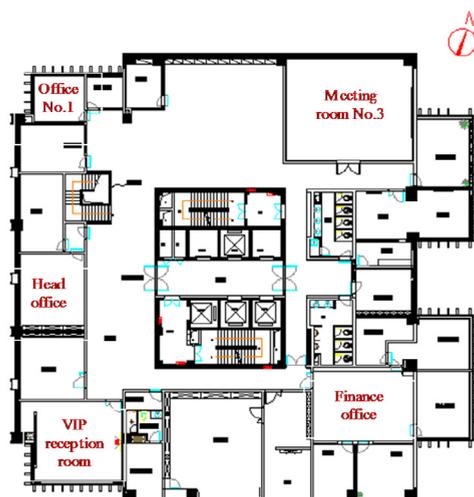


Fig. 3. The layout of the office building

Table 2. The room volume and area of the main decoration materials

Room Name	Meeting room No.3	Office No. 1	Head office	VIP reception room	Finance office
Room volume (m ³)	228.5	41.3	46.2	152.7	193.9
Wood veneer of ceiling (m ²)	0	0	0	0	20.7
Wood veneer of wall (m ²)	40.5	0	0	17.4	0.0
Furniture (m ²)	122.0	17.7	28.1	14.4	64.6
Door (m ²)	5.6	3.1	3.6	3.5	3.9
Carpet (m ²)	80.5	14.5	16.3	53.8	68.3
White latex of ceiling (m ²)	0	0	0	0	20.7
White latex of wall (m ²)	46.1	3.1	3.6	20.9	3.9
White latex of furniture (m ²)	0	0	15.0	0	0
Carpet adhesive (m ²)	10.5	1.9	2.1	7.0	8.9
Wall paint (m ²)	79.4	14.5	16.3	86.0	43.6
Glass cement (m ²)	1.5	1.5	1.1	1.1	3.1

Table 3. Decoration time schedule of the office building

Material Name	Date	Time to the decoration begin	Material Name	Date	Time to the decoration begin
White latex of ceiling	2014/5/31	0 h	Carpet	2014/11/15	4032 h
Wood veneer of ceiling	2014/5/31	0h	Door	2014/10/21	3432 h
Wall paint	2014/8/27	2112 h	Carpet adhesive	2014/11/15	4032 h
Glass cement	2014/9/20	2688 h	Furniture	2014/11/20	4152 h
White latex of furniture	2014/9/28	2880 h	Occupancy time	2014/12/27	5040 h
White latex of wall	2014/10/2	2976 h	Field measurement	2015/1/31	5880 h
Wood veneer of wall	2014/10/2	2976 h			

Table 4. Emission parameters of each materials

Dry material							
Name	$D_m(m^2/s)$	K	$C_0(mg/m^3)$	Name	$D_m(m^2/s)$	K	$C_0(mg/m^3)$
Furniture	1.98×10^{-13}	4341	19492	Carpet	2.03×10^{-13}	3639	22201
Door	1.05×10^{-13}	3277	3277	Wood veneer	6.30×10^{-13}	580	2898
Wet material							

Name	$E_f(\text{mg}/\text{m}^2/\text{h})$	$k_f(1/\text{h})$	Name	$E_f(\text{mg}/\text{m}^2/\text{h})$	$k_f(1/\text{h})$
White latex of ceiling	0.0905	0.0086	Carpet adhesive	0.0716	0.0079
White latex of wall	0.0905	0.0086	Wall paint	0.1868	0.0200
White latex of furniture	0.0905	0.0086	Glass cement	0.0919	0.0110

3.2. VOC concentrations results

Formaldehyde concentrations of the target rooms are shown in Fig. 4. The start time of the building construction is corresponding to 0 h in the figure. Indoor formaldehyde concentrations increased when there was a new material introduced. Highest formaldehyde concentrations occurred after wall painting during the simulation duration. Formaldehyde concentrations exceeded the national standard limitation ($0.1 \text{ mg}/\text{m}^3$) right after the completion of building construction. The highest formaldehyde concentration occurred in office No. 1 and the lowest was the VIP reception room among all the target rooms.

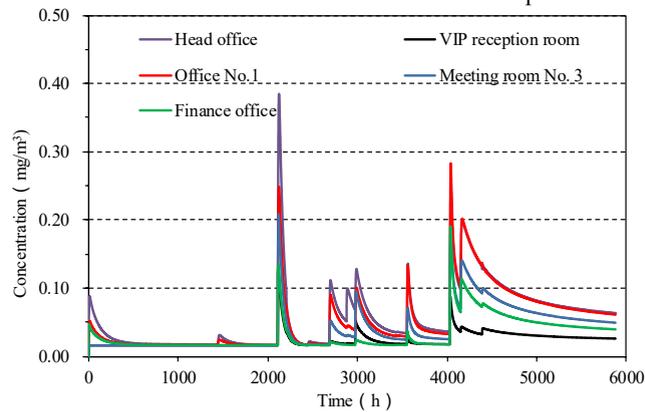


Fig. 4. Formaldehyde concentration variations of the target rooms

3.3. Comparison between simulation and measurement results

After the completion of building construction, indoor formaldehyde concentrations were measured after all windows and doors closed for 12 h. Comparison between the simulation results and measurement data is illustrated in Fig. 5. The differences between them were within $0.02 \text{ mg}/\text{m}^3$ (20%) in most occasion, which is acceptable for engineering application.

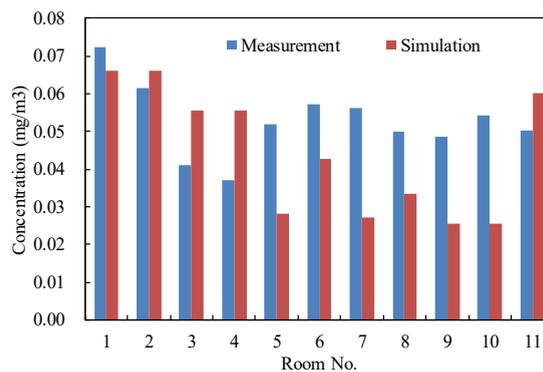


Fig. 5. Formaldehyde concentration comparison between the simulation and measurement results

4. Conclusions

In this paper, we introduced a pre-assessment and control tool for indoor air quality (PACT-IAQ). The different renovation stage, multiple emission sources/sinks, mechanical/natural ventilation and air cleaning were taken into consideration. Main influencing factors were analyzed and simplified to make it more suitable for engineering application. Framework and theoretical models of the tool were briefly introduced. The accuracy of the tool was validated by a multi-room office building. VOC concentrations were measured after the completion of building construction. The differences between simulation result and

measurement data were within 20% in most occasion, which is acceptable for engineering application. The main developments of the tool compared to other IAQ simulation software are that it is mainly based on the physical emission source and sink models, and the combined effects of temperature and humidity on material emissions could also be considered. The PACT-IAQ has promising application in indoor pollutant control.

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