A numerical model predicting indoor volatile organic compounds emissions from multiple building materials

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Abstract

There have been many studies on the model of volatile organic compounds (VOCs) emissions from individual dry building material and have been validated in the chamber. Actually, VOCs emitted from multiple dry building materials simultaneously indoor. The concentration of VOCs indoor increases and will inhibit the VOCs emission of dry building materials indoor. This paper developed a new model predicting indoor VOCs concentrations caused by simultaneous emissions from multiple dry building materials, with a consideration

of impact from dynamic VOCs concentrations on the emission rate. The model has been used to predict the VOCs emissions from a combination of medium density fiberboard (MDF) and consolidated compound floor (CCF) simultaneously. The study demonstrated a good prediction performance of the newly proposed model, against field experimental data. The study also showed that when multiple dry building materials emit pollutants in a common space, a mutual inhibition effect could be observed. Furthermore, when multiple dry building materials emit VOCs simultaneously, the change of VOCs concentrations in the air followed the trends of VOCs emissions from building materials with higher initial concentration (C_0), diffusion coefficient (D_m) and the partition coefficient (K_{ma}).

Keywords: Volatile Organic Compounds; Multiple dry building materials; Dynamic model; Initial concentration; Diffusion coefficient; Partition coefficient

Highlights:

- The model can predict VOCs concentration indoor.
- The mutual inhibition effect can be reflected
- The influence of three key parameters on indoor concentration of VOCs are analyzed.
- Can therefore reduce the health risks of people exposed to VOCs.

Acknowledgments

Funding: This work was supported by the National Key Research and Development Program of China [grant number 2017YFC0702700]; The 111 Project [grant number B13041]; and the Fundamental Research Funds for the Central Universities [Project NO.2018CDJDCH0015].

1: Introduction

People spending long time in rooms with poor indoor air quality would exhibit a variety of pathological reactions, such as Sick Building Syndrome (SBS), mainly due to the emitted Volatile Organic Compounds (VOCs) from building construction materials and furniture(J. TEN BRINKE. 1998). To provide comfortable and healthy living/working environment, indoor air quality has become a key research area globally.

VOCs have clear adverse effects on human's respiratory, cardiovascular and nervous systems, and may even cause cancer(L. Mølhave. 1989). To improve indoor air quality, it is necessary to gain a better understanding on the mechanism and characteristics of VOCs emissions from building construction materials. This formed a basic need for calculating indoor VOCs concentration and determining required fresh air volume, airflow organization and air purification equipment.

Accurate models predicting indoor VOCs emissions are essential for determining indoor pollutant concentrations and occupant exposure(WANG 2006). Existing emission models are typically belonging to one of the following types: empirical, semi-empirical or mass transfer. Based on a large number of experiments on VOCs emissions, researchers have established many empirical or semi-empirical models to describe VOCs emissions from different materials(Matthews T G 1987; Colombo A 1987; Clausen P A 1993), represented by either first-order

attenuation models or exponential decay models(Zhu J P 2001). The former models were the most widely used empirical models(Clausen P A 1993; Dunn L E. 1987). Empirical models are generally with simple forms but with limitations from experimental conditions. Therefore when being used for predictions, correction coefficients are usually needed(Zhao D 2002).

Entering the new century, analytical models based on mass transfer mechanism have become the most popular and widely used method to form VOCs emission models. Little et al.(Little J C 1994) firstly proposed an analytical model for predicting VOCs emissions from Single-layer homogeneous material. The model, however, neglects the convective mass transfer resistance between building materials and surrounding air, which gave prediction errors(Xu Y 2003). Huang and Haghighat (Huang and Haghighat 2002) took the convective mass transfer resistance into account in their model; they assumed the VOC concentration in the air to be zero to derive an analytical solution. This is not always justified under real conditions; they also provide a numerical solution based on finite difference method. Xu and Zhang (Xu Y 2003) develop a new model without the two preceding models assumption from a mass transfer perspective, and obtained an analytical solution. However, Xu and Zhang's solution is not fully explicit analytical solution. Deng and Kim (Deng B Q and Kim C N 2004) developed a fully analytical model considering both diffusion in the materials and mass transfer through the air boundary layer. VOC emissions from building materials that conform to the model assumptions can therefore be calculated by explicit formulae.

In addition to these models for single-layer homogeneous material with one surface that emits VOC to air, some researchers (Wang and Zhang, 2006; Kumar and Little, 2003 ; Li and Niu, 2007 60; Qian et al. 2007 ; Yuan et al. 2007; Deng et al. 2010) developed models for multi-layer homogeneous material, some researchers(Wang et al. 2006; Hu et al. 2007) developed models for materials with two emission surfaces and some researchers(Murakami et al. 2003; Lee et al. (2005); Xiong et al. 2008) developed models for materials with porous materials.

All models mentioned above were developed for predicting VOCs emissions of single building material. In actual buildings, however, there will be many different dry building materials existing in the same room. When a variety of dry building materials are releasing VOCs at the same time, the indoor VOCs concentration will increase, and in reverse this increased concentration will inhibit the VOCs release from individual building materials. Therefore, the whole process is dynamically changing. Therefore, if the above-mentioned models developed for predicting VOCs emissions from a single building material are used to separately solve the VOCs concentration emitted by each dry building material and the VOCs concentration of indoor obtained by superposition will be too large. Therefore, the final indoor VOCs concentration should not be obtained by simply superimposing the concentrations of pollutants emitted from individual dry building materials(Cheng T 2002).

In this paper, the simultaneous emission of VOCs from multiple single-layer materials coexisting in indoor environment is developed. A numerical solution of the indoor concentration is derived using the finite difference method. The accuracy of the numerical solution was verified by measuring VOCs emission of MDF and CCF in the chamber. In addition, C0, D_m and K_{ma} of different dry building materials affecting concentration of VOCs indoor have been discussed.

2: Model Development

In the model proposed in this study, the number of thin layer materials were defined as *i*. The mass transfer equations were combined with the mass conservation equations. Since the initial concentration of this model was assumed to be a constant, which would not last for a long time, the model is applicable for short-term predictions only. The model can be used as a quick and useful tool for predicting indoor VOCs concentrations at any time in newly refurbished/decorated homes, giving occupants ideas on the indoor pollutant level of their living environment. When developing the model, it was also necessary to determine the partition coefficient (K), the diffusion coefficient (D) and the initial concentration(C_0) in each material, and this was done using the C-History method(Xiong J 2011).

2.1 Model formation

The model developed here assumed that VOCs were simultaneously emitted from several thin homogeneous materials. The VOCs diffusion in dry material was assumed to be one-dimensional, i.e. from the material to the air. For a homogeneous material with uniform initial VOCs concentration, the transient VOCs diffusion could be described by the following diffusion equation,

$$\frac{\partial C_m}{\partial t} = D_m \frac{\partial^2 C_m}{\partial y^2} \quad (1)$$

where C_m was the concentration of the VOCs in the thin layer material; t was time; y was linear distance; D_m was diffusion coefficient of the thin layer material.

The number of thin layer materials were defined as i in the proposed model. Eq. (1) was used for each thin layer material by Equation 2,

$$\frac{\partial C_{m,i}}{\partial t} = D_{m,i} \frac{\partial^2 C_{m,\mathrm{i}}}{\partial y^2} \quad (2)$$

where i represented the ith thin layer material, with initial condition given as:

$$C_{m,i|t=0} = C_{0,i} \text{ for } 0 \leqq y \leqq \delta_i \quad (3)$$

where $C_{0,i}$ was the VOCs concentration at t=0 for the i^{th} thin layer material and δ_i was the thickness of the i^{th} thin layer material. For thin layer materials placed on the stainless steel floor of the chamber, the boundary condition was assumed to have no flux from the bottom of the thin layer materials. Therefore, since Equation (2) is subject to the boundary condition:

$$\left.\frac{\partial C_{m,i}}{\partial y}\right|_{y=0} = 0 \quad (4)$$

For the material-air interface, the emission of VOCs from the thin layer materials was determined by Equation 5,

$$-D_{m,i}\left.\frac{\partial C_{m,i}}{\partial y}\right|_{y=\delta_i} = h\left(C_{ai,i} - C_a\right) \quad (5)$$

where h was the mean gas-phase mass transfer coefficient, assumed to be the same for all materials; $C_{ai,i}$ was the VOCs concentration of material-air interface in the i^{th} thin layer material (μg m^{-3}), and C_a was the average VOCs concentration in the chamber.

Equilibrium was assumed to exist between the VOCs concentrations at the surface of thin layer materials and that in the chamber. At the boundary, Equation 6 existed:

$$C_{m,i}\big|_{y=\delta_i} = K_{ma,i}C_{ai,i} \quad (6)$$

where $K_{ma,i}$ was the i^{th} material-air partition coefficient.

C_a in equation (5) could be derived from the mass balance of VOCs in the chamber. Because the inlet VOCs concentration was assumed as zero, the mass balance equation was written as,

$$V\frac{\partial C_a}{\partial t} = -\mathrm{A}D_m\left.\frac{\partial C_m}{\partial y}\right|_{y=\delta} - \mathrm{Q}C_a \quad (7)$$

When VOCs are simultaneously emitted from multiple dry building materials, C_a changes significantly. According to Equation (5), the value of C_a also affects the state of VOCs inside

the building materials. Therefore, the VOCs concentration in the chamber cannot be calculated by mathematically superimposing the VOCs emissions from individual building materials. The governing equation describing the transient mass balance for all thin layer materials was defined as follows:

$$\mathrm{V}\frac{\partial C_a}{\partial \mathrm{t}} = -QC_a - A_1 D_{m,1}\left.\frac{\partial C_{m,1}}{\partial y}\right|_{y=\delta_1} - A_2 D_{m,2}\left.\frac{\partial C_{m,2}}{\partial y}\right|_{y=\delta_2} \ldots - A_i D_{m,i}\left.\frac{\partial C_{m,i}}{\partial y}\right|_{y=\delta_i}, \mathrm{i} = 1,2,3 \ldots \quad (8)$$

where V was the volume of the chamber (m^3); Q was the ventilated quantity ($m^3\ h^{-1}$), and A_i was the area of the i^{th} building material.

The initial concentration (C_0) was assumed to be constant in this model. Since this assumption is only applicable for short time periods, this model is only suitable for short-term predictions.

2.2 Numerical solutions

The solution was coupled with the concentration in the air, which was an unknown function of time. The concentration in the material and the mass balance equation in the air must be solved simultaneously by finite difference technique. Saul'ev finite difference method has a semi-implicit format, which not only solves the problem that the explicit format is not easy to stabilize, but also avoids the complicated calculation of the implicit format. In the article, the Saul'ev finite difference method was used to solve the above model, and Equations (2) to (7)

were transformed into following equations,

(a) VOCs concentration in the material:

Based on the Saul'ev finite difference method, equation (2) was converted into:

$$\mathrm{C}_{m,1}{}_{j}^{k+1} = \frac{1-D_{m,1}\lambda}{1+D_{m,1}\lambda}\mathrm{C}_{m,1}{}_{j}^{k} + \frac{D_{m,1}\lambda}{1+D_{m,1}\lambda}\left(\mathrm{C}_{m,1}{}_{j-1}^{k+1} + \mathrm{C}_{m,1}{}_{j+1}^{k}\right);\ \mathrm{k} = 0,1,\ldots;\mathrm{j} = 1,2\ldots,n_1 - 1;$$

$$\mathrm{C}_{m,2}{}_{j}^{k+1} = \frac{1-D_{m,2}\lambda}{1+D_{m,2}\lambda}\mathrm{C}_{m,2}{}_{j}^{k} + \frac{D_{m,2}\lambda}{1+D_{m,2}\lambda}\left(\mathrm{C}_{m,2}{}_{j-1}^{k+1} + \mathrm{C}_{m,2}{}_{j+1}^{k}\right);\ \mathrm{k} = 0,1,\ldots;\mathrm{j} = 1,2\ldots,n_2 - 1;$$

…

$$\mathrm{C}_{m,\mathrm{i}}{}_{j}^{k+1} = \frac{1-D_{m,\mathrm{i}}\lambda}{1+D_{m,\mathrm{i}}\lambda}\mathrm{C}_{m,\mathrm{i}}{}_{j}^{k} + \frac{D_{m,\mathrm{i}}\lambda}{1+D_{m,\mathrm{i}}\lambda}\left(\mathrm{C}_{m,\mathrm{j}}{}_{j-1}^{k+1} + \mathrm{C}_{m,\mathrm{i}}{}_{j+1}^{k}\right);\ \mathrm{k} = 0,1,\ldots;\mathrm{j} = 1,2\ldots,n_i - 1;\ (8)$$

(b) VOCs concentration in indoor air:

Based on Trapezoidal method, equation (2) was converted into:

$$\frac{\partial C_a}{\partial t} = -NC_a - L_1\left(hC_a - h\frac{C_{m,1}\big|_{y=\delta_1}}{K_{ma,1}}\right) - L_2\left(hC_a - h\frac{C_{m,2}\big|_{y=\delta_2}}{K_{ma,2}}\right)\ldots - L_i\left(hC_a - h\frac{C_{m,i}\big|_{y=\delta_i}}{K_{ma,i}}\right)$$

$$= -(N + L_1h + L_2h + \cdots + L_ih)C_a + \frac{L_1h}{K_{ma,1}}C_{m,1}\big|_{y=\delta_1} + \frac{L_2h}{K_{ma,2}}C_{m,2}\big|_{y=\delta_2} + \cdots + \frac{L_ih}{K_{ma,i}}C_{m,i}\big|_{y=\delta_i}$$

$$\rightarrow\quad C_{\mathrm{a}}^{k+1} - C_a^k = \frac{\tau}{2}\left[\frac{L_1h}{K_{ma,1}}\mathrm{C}_{m,1}{}_{n_1}^{k+1} + \frac{L_2h}{K_{ma,2}}\mathrm{C}_{m,2}{}_{n_2}^{k+1} + \cdots + \frac{L_ih}{K_{ma,i}}\mathrm{C}_{m,\mathrm{i}}{}_{n_i}^{k+1} - \Big(N + L_1h + L_2h + \cdots + L_ih\Big)C_{\mathrm{a}}^{k+1} + \frac{L_1h}{K_{ma,1}}\mathrm{C}_{m,1}{}_{n_1}^{k} + \frac{L_2h}{K_{ma,2}}\mathrm{C}_{m,2}{}_{n_2}^{k} + \cdots + \frac{L_ih}{K_{ma,i}}\mathrm{C}_{m,\mathrm{i}}{}_{n_i}^{k} - (N + L_1h + L_2h + \cdots + L_ih)C_a^k\right];$$

$$\rightarrow\quad \left[1 + \frac{\tau}{2}(N + L_1h + L_2h + \cdots + L_ih)\right]C_a^{k+1} = \left[1 - \frac{\tau}{2}(N + L_1h + L_2h + \cdots + L_ih)\right]C_a^k + \frac{\tau}{2}\times\frac{L_1h}{K_{am,1}}\left(\mathrm{C}_{m,1}{}_{n_1}^{k+1} + \mathrm{C}_{m,1}{}_{n_1}^{k}\right) + \frac{\tau}{2}\times\frac{L_2h}{K_{am,2}}\left(\mathrm{C}_{m,2}{}_{n_2}^{k+1} + \mathrm{C}_{m,2}{}_{n_2}^{k}\right) + \cdots + \frac{\tau}{2}\times\frac{L_ih}{K_{am,i}}\left(\mathrm{C}_{m,\mathrm{i}}{}_{n_i}^{k+1} + \mathrm{C}_{m,\mathrm{i}}{}_{n_i}^{k}\right)$$

211 k = 0,1,2 … (9)

212 (c) VOCs concentration at the surface of the material:

213 According to formula (3) and formula (5), assuming that the diffusion equation is also true on
214 the boundary, the difference format of the inner point can be extended to the boundary.
215 Considering the previous difference format:

216 $$C_{m,1}{}_0^{k+1} = \left(1 - 2\lambda_1 D_{m,1}\right) C_{m,1}{}_0^{k} + 2\lambda_1 D_{m,1} C_{m,1}{}_1^{k}$$

217 $$C_{m,2}{}_0^{k+1} = \left(1 - 2\lambda_2 D_{m,2}\right) C_{m,2}{}_0^{k} + 2\lambda_2 D_{m,2} C_{m,2}{}_1^{k}$$

218 …

219 $$C_{m,i}{}_0^{k+1} = \left(1 - 2\lambda_i D_{m,i}\right) C_{m,i}{}_0^{k} + 2\lambda_i D_{m,i} C_{m,i}{}_1^{k};\ k = 0,1, \ldots$$

220 $$C_{m,1}{}_{n_1}^{k+1} = \left[1 - 2\lambda_1 D_{m,1}\left(1 + \frac{h_1 \times h}{D_{m,1} K_{ma,1}}\right)\right] C_{m,1}{}_{n_1}^{k} + 2\lambda_1 D_{m,1} C_{m,1}{}_{n_1-1}^{k} + 2\lambda_1 h_1 \times h {C_a}^{k}$$

221 $$C_{m,2}{}_{n_2}^{k+1} = \left[1 - 2\lambda_2 D_{m,2}\left(1 + \frac{h_2 \times h}{D_{m,2} K_{ma,2}}\right)\right] C_{m,2}{}_{n_2}^{k} + 2\lambda_2 D_{m,2} C_{m,2}{}_{n_2-1}^{k} + 2\lambda_2 h_2 \times h {C_a}^{k}$$

222 $$C_{m,i}{}_{n_i}^{k+1} = \left[1 - 2\lambda_i D_{m,i}\left(1 + \frac{h_2 \times h}{D_{m,i} K_{ma,i}}\right)\right] C_{m,i}{}_{n_i}^{k} + 2\lambda_i D_{m,i} C_{m,i}{}_{n_i-1}^{k} + 2\lambda_i h_i \times h {C_a}^{k}$$

223 where $\lambda_i = {\tau}/{h_i^2},\ h_i = {\delta_i}/{n_i}$ (10)

224

225 ***2.3 Estimation of key parameters***

226 To use the model proposed in this study, there were four key parameters: K_{ma}, D_m C_0 and h
227 in the material, and in existing studies the former three have been determined using different
228 methods (Wang X 2009; Xiong J 2011; Huang, Xiong J 2013; Li F 2005). In this study, the C-history

229 method proposed by Xiong et al. (Xiong J 2011) was adopted. The C-history method involves
230 some steps: 1) placing the building materials in a chamber; 2) recording the curve of
231 concentration change in the chamber; 3) solving the emission characteristic parameters (C_0,
232 D_m and K_{ma}) for the dry building materials through the least squares fitting method. Since
233 wood-based panels are the main source of indoor VOC, and this experiment studied the
234 emission law of multiple dry building materials, MDF and CCF which are widely used in
235 furniture and decoration were chosen as subjects. Before the experiments, MDF and CCF were
236 processed according to the method specified in (ISO 16000-11). As required by the C-History
237 method, one specimen of each building material was placed in a chamber respectively.
238 According to (ISO 12460-1), a chamber with a volume of 1m^3 has been used for testing
239 formaldehyde emissions from CCF and MDF in this study. The measurement method adopted
240 here for formaldehyde was known as the MBTH (3-methyl-2-benzothiazolinone hydrazine)
241 spectrophotometric method, as defined in the Chinese GB/T 18204.26
242 standard(GB/T18204.26-2000). The formaldehyde emission was monitored with fitted linear
243 curves shown in Fig. 1. From the correlation coefficient (R^2) listed in Fig. 1, it could conclude
244 that the both fitted linear models have adequate performance, according to (ASTM Standard
245 D5157-97). Table 1 lists the values for C_0, D_m and K_{ma} from the experiment.
246

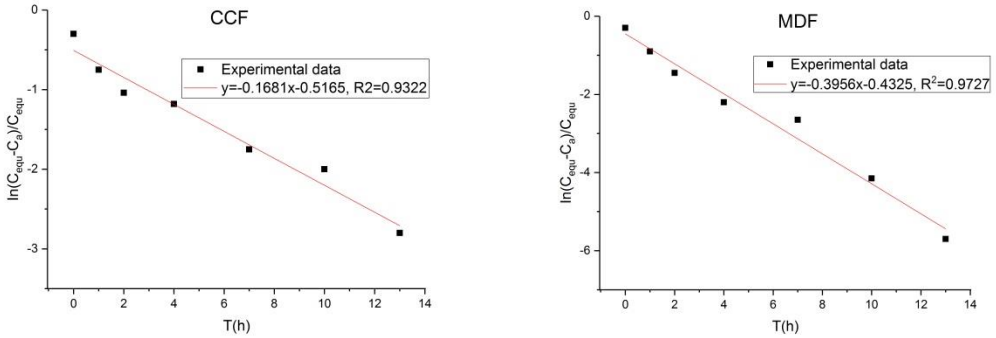


Fig. 1: Fitted linear curves of chamber formaldehyde concentrations for CCF and MDF separately

Table 1: Characteristic parameters for formaldehyde in the test specimens

Material	C_0 (μg m^{-3})	D (m^2 s^{-1})	K
CCF	2.89×10^{6}	8.9×10^{-11}	1033
MDF	1.32×10^{7}	2.32×10^{-10}	820

Some empirical relations can be adopted to solve *h.* For laminar flow, these exists:

$$Sh = 0.664Sc^{1/3}Re^{1/2}$$

Where $Sh = hl/D_a$, $Sc = v/D_a$, $Re = ul/v$

Sh is Sherwood number, Sc is Schmidt number, Re is Reynolds number, l was the characteristic length of the material, v was the kinematic viscosity of the air, and u was the velocity of the air over the material. According to this empirical relation, h was used in the present model to be 2.3×10^{-3} m/s.

3: Model Validation

3.1 Experimental materials and conditions

Due to the wide usage of wooden boards in furniture, floors and decorative materials in China, two common board types, i.e. MDF and CCF were chosen for the analysis, as tested in the above section. The specimens were cut into the same dimensions as $0.5 \times 0.5 \times 0.012 m^3$. Both types of experimental materials required proper treatment prior to and during the test according to (ISO16000-9). Before the experiment, both MDF and CCF were sealed in a bag using tin foil for approximately 20 days to give a uniform distribution of pollutants inside the building materials. As described in Section 2, their C_0, D_m and K_{ma} values were obtained and calculated based on experiments. ISO standards(ISO16000-9., ISO12460-1.) have suggested a method testing formaldehyde and VOCs in environmental chambers with various sizes. According to (ISO 12460-1), a chamber with a volume of $1m^3$ has been used for testing formaldehyde emissions from CCF and MDF in this study. During the experiment, temperature, relative humidity (RH) and air exchange rate in the chamber were maintained at 23±0.5 °C, 50%±5% and 1 ACH, respectively(ISO16000-9.).

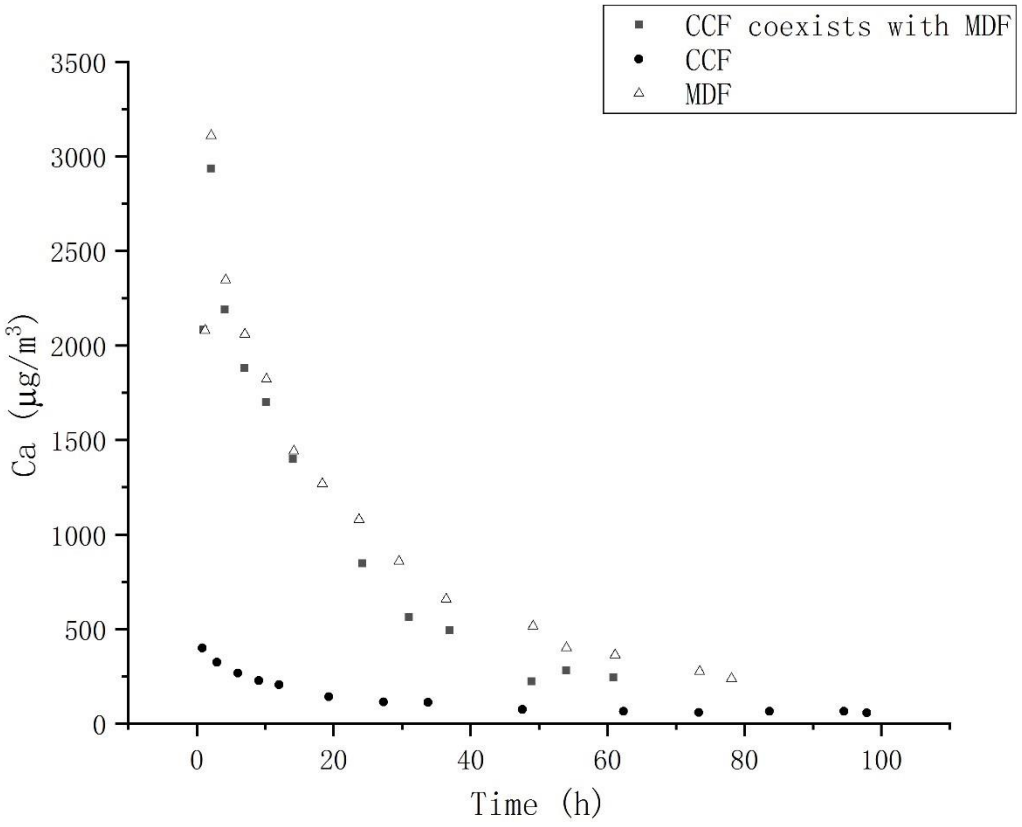
Formaldehyde was selected as the target chemical pollutant for this study, as it is a major pollutant found in building materials and a common indoor air pollutant in many countries(Zhang L 2009). The measurement method adopted here for formaldehyde was known as the MBTH (3-methyl-2-benzothiazolinone hydrazine) spectrophotometric method, as

279 defined in the Chinese GB/T 18204.26 standard(GB/T18204.26-2000). During the experiment,
280 the flow rate was measured at 0.5L/min for both pre-sampling and post-sampling, based on a
281 sampling time of 20min. Chemical analysis was carried out right after each sampling work.
282 The whole experiment was consisted of three different VOCs emission tests, which were:

283 1. One piece of MDF was placed in the chamber and the concentration of formaldehyde
284 in the chamber was measured and recorded, until the data trend became stable;
285 2. One piece of CCF was placed in the chamber and the concentration of formaldehyde
286 in the chamber was measured and recorded, until the data trend became stable;
287 3. One piece of MDF and one piece of CCF were placed in the chamber and the
288 concentration of formaldehyde in the chamber was measured and recorded, until the data
289 trend became stable.

290 The first two experiments were designed to validate the model's performance on single material
291 and the last experiment was designed to validate its performance on multiple materials.
292
293 The experimental results of the three experiments are shown in Fig. 2. The test duration is about
294 100 hours. The concentration of formaldehyde became stable after 100 hours approximately. It
295 is found from the experimental results that although the concentration of formaldehyde
296 emission by MDF is much higher than CCF, in the case of integrated emission, significant
297 inhibition is still produced when CCF and MDF emitted formaldehyde together. In most cases,

298 the concentration of formaldehyde in chamber emitted by CCF coexists with MDF is slightly
299 lower than the concentration emitted by MDF alone.



300

301 **Fig. 2:** Summary of experimental results

302

303 ***3.2 Results***

304 The present model has been applied to the formaldehyde emission from CCF and MDF. The
305 building materials for both the Deng&Kim's model and the present model are single-layer
306 homogeneous materials, and the assumptions used in both models are the same. In addition to

this, the Deng&Kim's model obtained a fully analytical solution which is more accurate than the numerical solution. Therefore, the solution of Deng&Kim's model (Deng B Q and Kim C N 2004) is selected and compared with the experimental data and the solution of the present model. The indoor concentration of formaldehyde emission from CCF and MDF respectively are presented in Figs.3-4. It can be found that the predicted values from the present model had a good fit with the real measured values. Numerical solution of this model is in good agreement with experimental results. Therefore, the problem of pollutant emission of various building materials cannot be ignored.

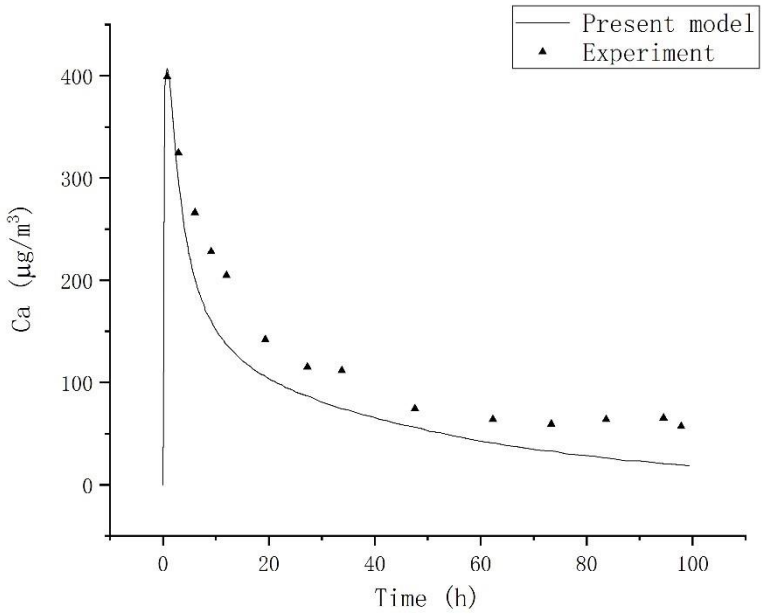
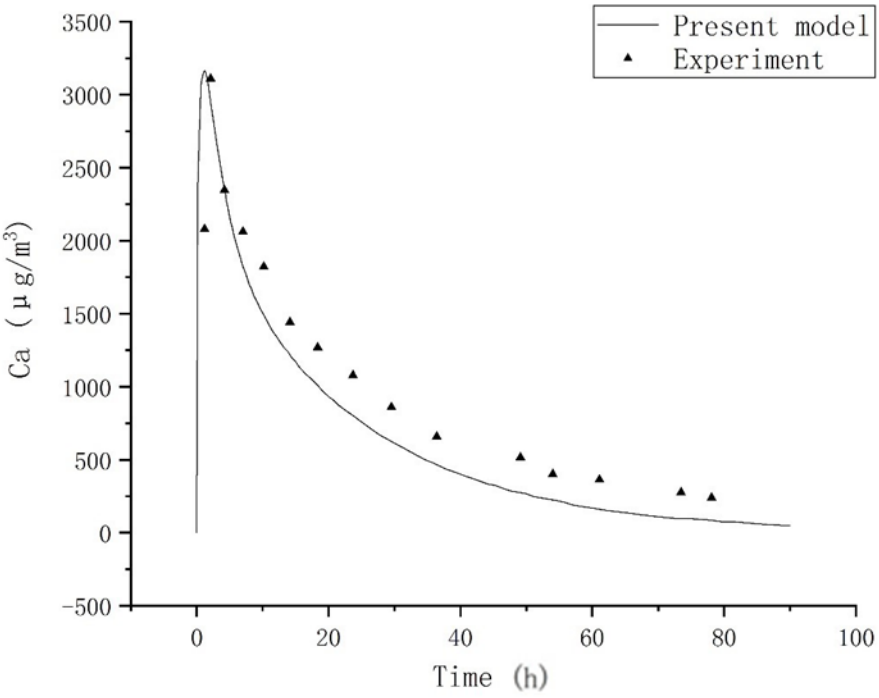


Fig. 3: Chamber concentration of formaldehyde emitted from CCF with time



318

319 **Fig. 4:** Chamber concentration of formaldehyde emitted from MDF with time

320

321 Fig.5 compares the results of the present model, the experimental results, and the results of
322 mathematical superposition using the Deng&Kim model(Deng B Q and Kim C N 2004) when the
323 CCF and MDF emitted formaldehyde together.

324

325 It can be seen from the figure that the application of the Deng&Kim model(Deng B Q and Kim
326 C N 2004) for a single building material to calculate the formaldehyde emission of the CCF and
327 MDF respectively, and the results of emission by CCF coexists with MDF obtained by
328 mathematical superposition cannot reflect the mutual inhibition of the existence of various

building materials. The results of the present model are in line with the experimental results. The present model can reflect the inhibition of formaldehyde emission from multiple building materials together.

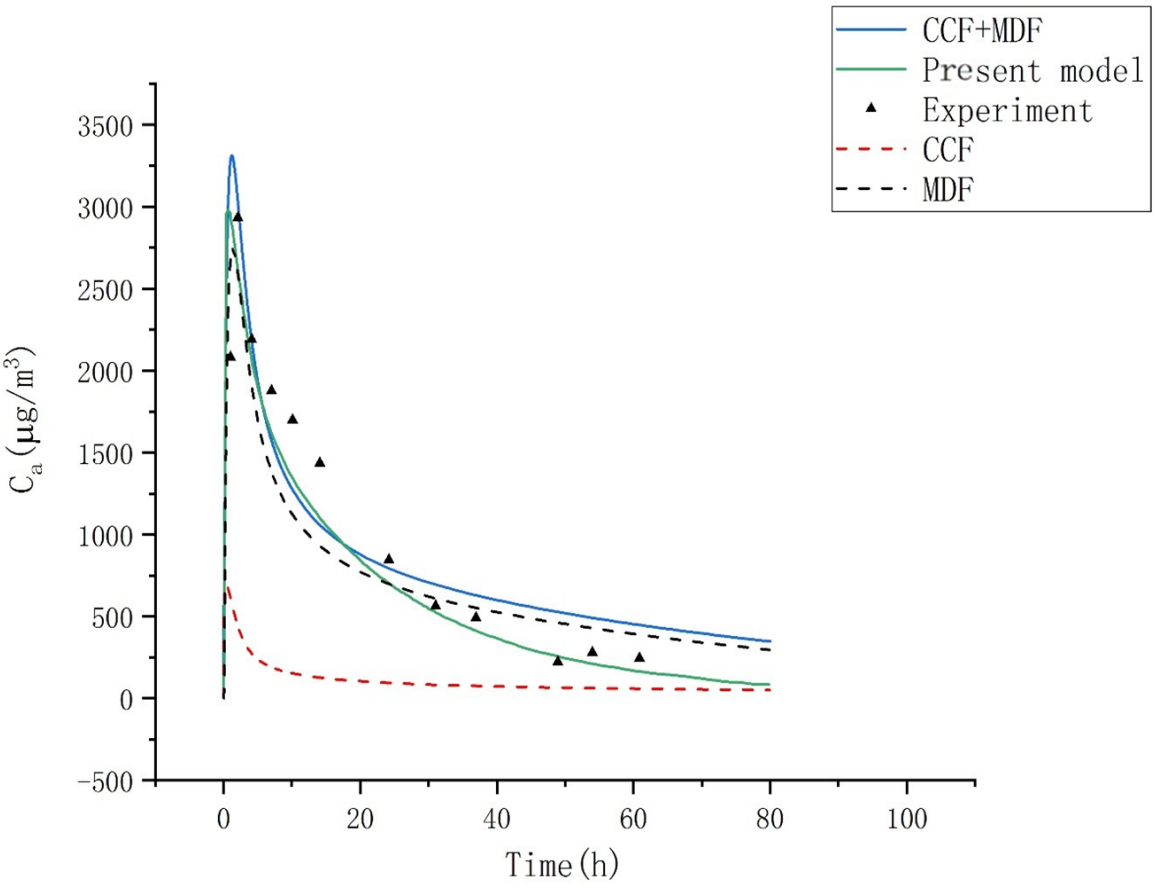
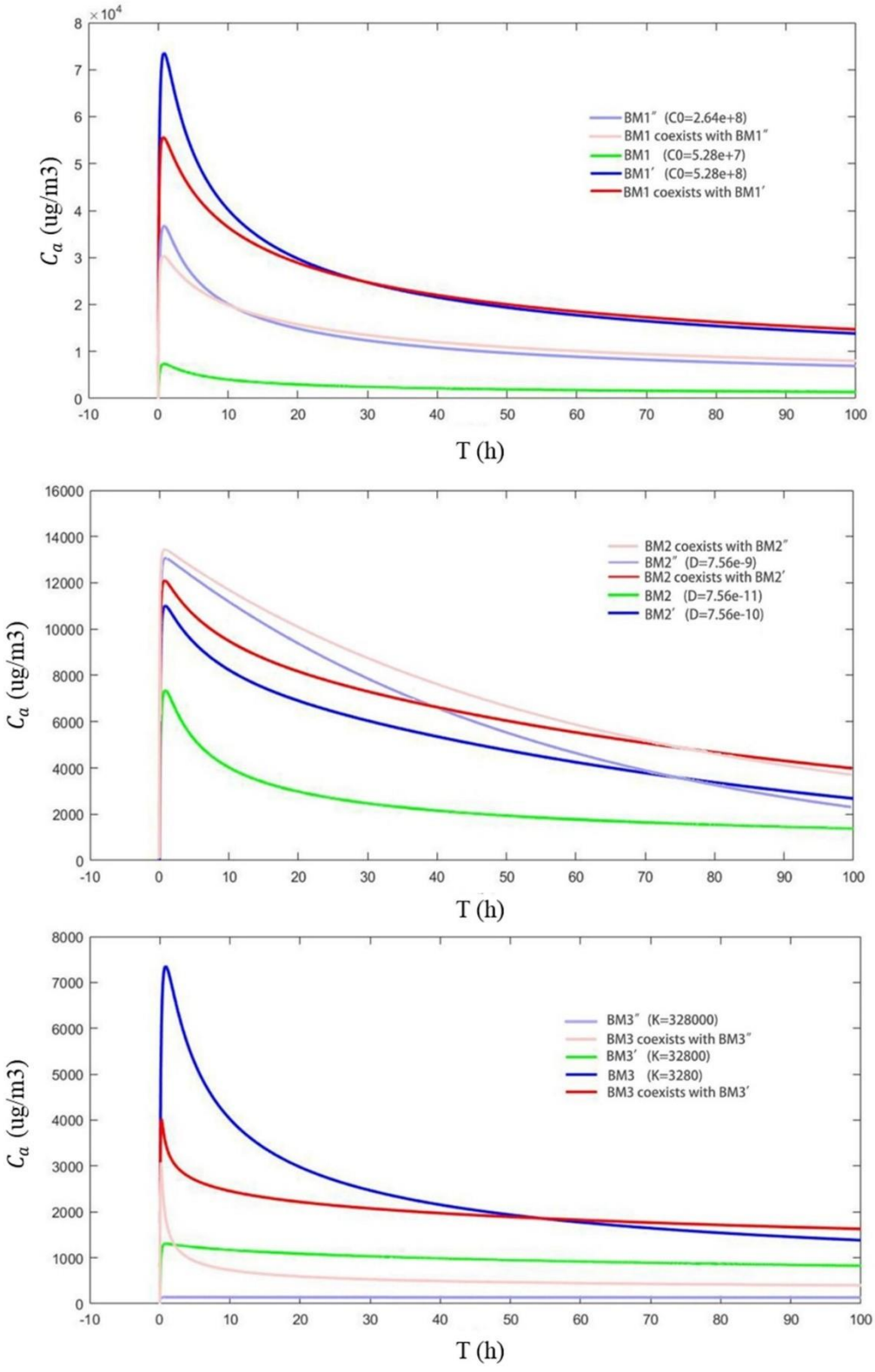


Fig. 5: chamber concentration of formaldehyde emitted from CCF and MDF with time. "CCF" and "MDF" are the simulation results of Deng&Kim for two kinds of plates respectively. "CCF+MDF" is the mathematical superposition of the results of CCF and MDF, and "Present model" is the simulation results of the coexistence of CCF and MDF by the present model

4: Discussions

Partition coefficient (K_{ma}), diffusion coefficient (D_m) and initial concentration (C_0) are main factors influencing VOCs emissions from building materials(Yang X 2001). In this study, three sets of simulations were carried out to determine the influences of these parameters on the VOCs concentrations from multiple dry building materials. In each experiment, both size and emission surface area were kept constant for the two types of building materials under investigation, but with varying key parameters. For both types, C_0, D_m and K_{ma} were set to $5.28\times10^7/5.28\times10^8/2.64\times10^8$ μg/m^3, $7.56\times10^{-11}/7.56\times10^{-10}/7.56\times10^{-9}$ m^2/s, and 3280/32800/328000, respectively. Fig. 6 shows the results from the simulations. According to Fig. 6, higher C_0 and D_m would lead to increased VOCs concentrations in the air, and higher K_{ma} gave lowered VOCs concentrations. When there were more than one type of dry building materials existing, the change of VOCs concentrations in the air would be closer to that of the dry building material with higher C_0, higher D_m and lower K_{ma}, especially at later stages. Furthermore, existence of other dry building materials would partly decrease the VOCs emission of a single building material, when it existed alone. Additionally, a material with lower VOCs emission could act as a pollutant balancer at early stages of VOCs emissions, as reflected by Figs. 6 (a) and (c).

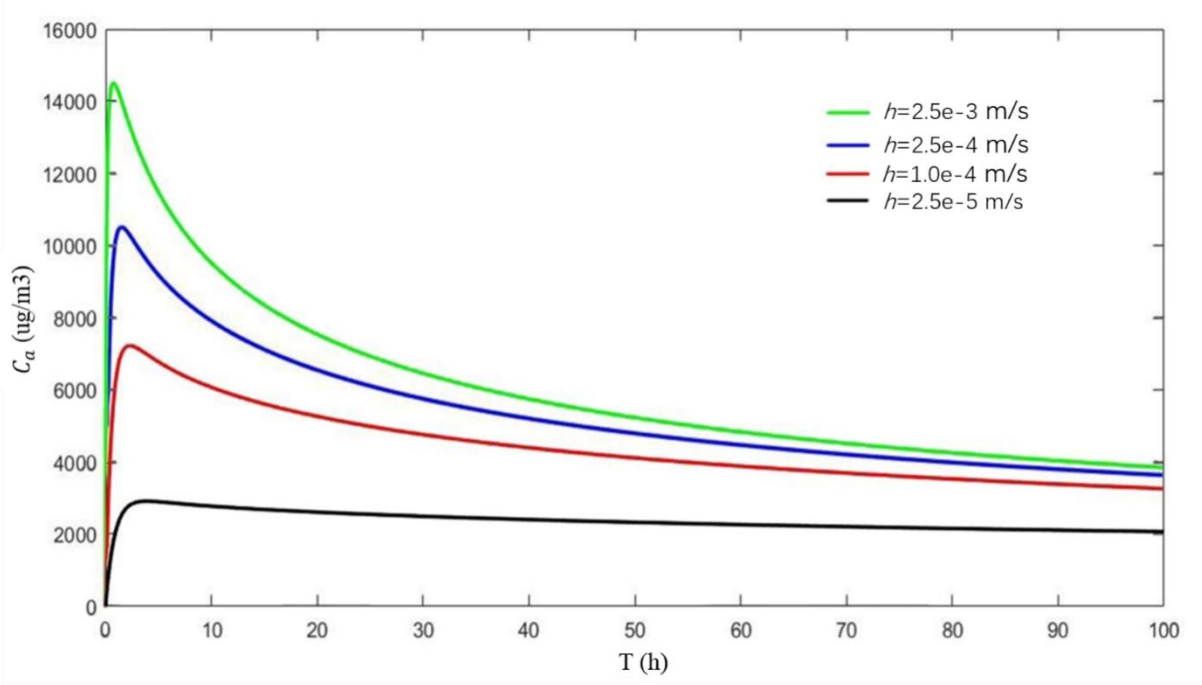


357

358 **Fig. 6** Comparison of VOC concentrations over time for different values of a) C_0 (BM1)**,** b) D_m (BM2),

and K_{ma} (BM3)

Using the model developed, the effects of both convective mass-transfer coefficient (*h*) and air exchange rate (N) on VOCs emissions from multiple building materials were analyzed as well. Using two types of building materials as an example, it was found that *h* only had significant influences at the start of the VOCs emission process but at later stages the influences from this parameter can be neglected. When the magnitude of *h* was less than 10^{-4}, the VOCs emission would reach steady state quickly (Fig. 7). Different values of N would affect the whole VOCs emission process of multiple dry building materials (Fig. 8). At the late stages of VOCs emission, it was observed that the VOCs concentration in the air performed a linear correlation with N.



371

372 **Fig. 7** Comparison of VOC concentrations with varying convective mass-transfer coefficient (*h*)

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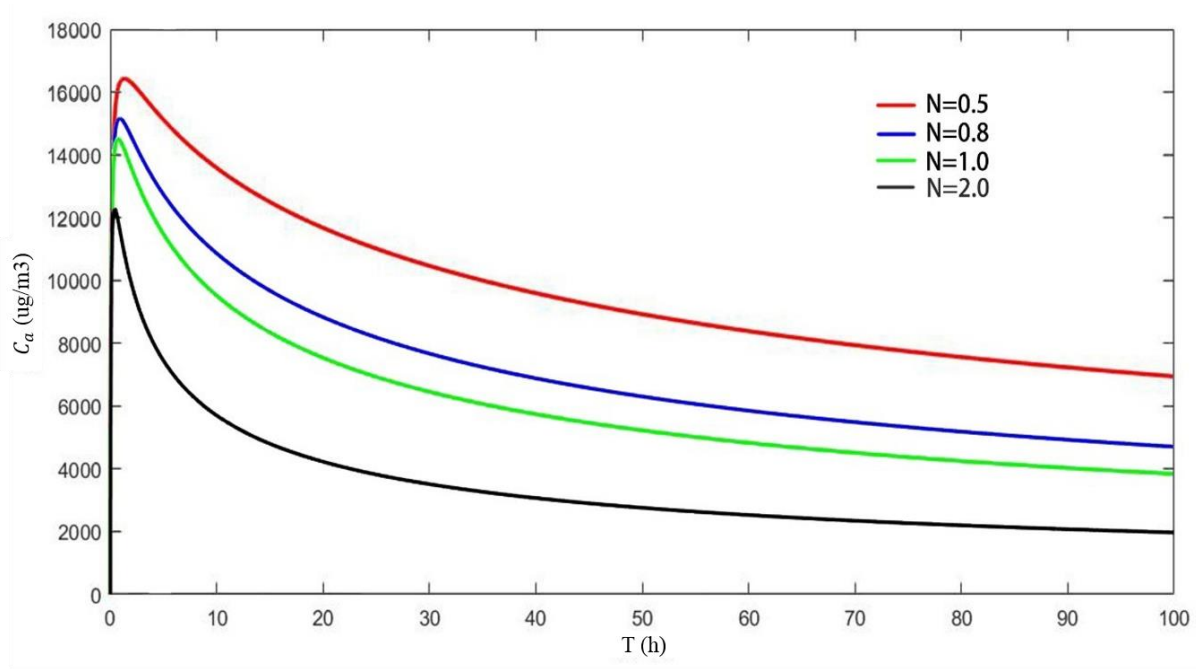

374

375 **Fig. 8** Comparison of VOC concentrations with varying air exchange rate (N)

5: Conclusion

As indoor building materials release a large amount of pollutants into the air, the increase in indoor air pollutant concentration will endanger people's health. Therefore, it is necessary to predict the indoor VOCs concentration emitted by indoor building materials. At present, the indoor air quality prediction platform generally adopts the empirical formula or the emission model. But the empirical coefficient in the empirical formula is obtained by fitting the experimental data of emission experiment in the chamber. In the actual environment, the correction coefficient needs to be considered. The emission model only considers the mass transfer process of a single building material, and does not consider the suppression between various building materials. Using the emission model to calculate the VOCs emissions of each building material and superimposing will directly lead to huge deviation of indoor VOCs concentration.

A mathematical model and a new numerical solution were established to predict the concentration of VOCs indoor emitted from multiple materials in buildings. The model considers the inhibitory effect that occurs when various building materials emit VOCs at the same time and proposes a numerical solution for this problem. The model predictions show a good agreement with experimental data for two VOCs emission sources (MDF and CCF). The

395 proposed model can be used to predict VOCs concentrations in the air for a newly decorated
396 room, thereby reducing the health risks of exposure to VOCs.
397
398 When multiple dry building materials emit pollutants in the same space, a mutual inhibition
399 effect is observed; this effect requires further attention. Additionally, when multiple dry
400 building materials emit VOCs simultaneously, the VOCs concentration change is similar to the
401 VOCs emission trend of building materials with higher C_0, D_m, and K_{ma} values. The emission
402 of VOCs from building materials with lower C_0 values is inhibited, and the VOCs in the air is
403 even adsorbed. D_m does not significantly affect the inhibition of different building materials,
404 but it does affect the maximum concentration of VOCs. The K_{ma} value also has a significant
405 impact on the inhibition of different building materials; VOCs emission is significantly
406 inhibited at a low K_{ma} value and an adsorption effect may even be observed. The N value has
407 a more obvious impact on the coexistence of multiple dry building materials, especially in the
408 later stage of VOCs emission, which indicates a linear relationship. The *h* value does not have
409 a significant impact on the later stage of VOCs emission from multiple building materials.
410

411 **Declaration of interest**

412 The authors report no conflicts of interest.
413

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