atmosphere

MDPI

Article

Study on the Effect of an Intermittent Ventilation Strategy on Controlling Formaldehyde Concentrations in Office Rooms

Baoping Xu [1,*], Yuekang Liu [1], Yanzhe Dou [1], Ling Hao [2], Xi Wang [1] and Jianyin Xiong [3,*]

[1] School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China; liu.yk@bdia.com.cn (Y.L.); 120191470108@ncepu.edu.cn (Y.D.); wx@ncepu.edu.cn (X.W.)
[2] Beijing Kezhu Construction Engineering Co., Ltd., Beijing 100086, China; haoling@kezhuwuye.com
[3] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
* Correspondence: xubp@ncepu.edu.cn (B.X.); xiongjy@bit.edu.cn (J.X.)

Abstract: Material emission and ventilation are two aspects influencing indoor air quality. In this study, a model predictive control (MPC) strategy is proposed for intermittent ventilation system in office buildings, to achieve a healthy indoor environment. The strategy is based on a dynamic model for predicting emissions of volatile organic compounds (VOCs) from materials. The key parameters of formaldehyde from panel furniture in the model are obtained by an improved C-history method and large-scale chamber experiments. The effectiveness of the determined key parameters is validated, which are then used to predict the formaldehyde concentration variation and the pre-ventilation time in a typical office room. In addition, the influence of some main factors (i.e., vacant time, loading ratio, air change rate) on the pre-ventilation time is analyzed. Results indicate that the pre-ventilation time of the intermittent ventilation system ranges from several minutes to several hours. The pre-ventilation time decreases exponentially with the increase in the vacant time, the air change rate, and with the decrease in the loading ratio. When the loading ratio of the furniture is 0.30 m^2/m^3 and the vacant time is 100 days, the required pre-ventilation time approaches zero. Results further reveal that an air change rate of 2 h^{-1} is the most effective means for rapid removal of indoor formaldehyde for the cases studied. The proposed strategy should be helpful for achieving effective indoor pollution control.

Keywords: intermittent ventilation; furniture; formaldehyde emission; pre-ventilation time; model predictive control

check for updates

Citation: Xu, B.; Liu, Y.; Dou, Y.; Hao, L.; Wang, X.; Xiong, J. Study on the Effect of an Intermittent Ventilation Strategy on Controlling Formaldehyde Concentrations in Office Rooms. *Atmosphere* **2022**, *13*, 102. https://doi.org/10.3390/atmos13010102

Academic Editors: Jia Xing, Jim Kelly, Jun Zhao, Yuqiang Zhang and Yun Zhu

Received: 24 November 2021
Accepted: 6 January 2022
Published: 9 January 2022

1. Introduction

People spend 87% of their time indoors [1]. Indoor air pollution has been recognized as one of the main risks to human health [2–4]. A recent survey [5] showed that indoor air pollution emerges in about 80% of office buildings, and 69% of the office staff are not satisfied with the current office environment. Much attention has been paid to the indoor pollution caused by the emissions of volatile organic compounds (VOCs) from building materials and furniture [6–11]. Numerous studies have revealed that one of the most effective ways to dilute VOCs is by ventilation [12–15]. In addition, air purification is also important for indoor pollution control [16–18].

For the study on the VOC emission characteristics, it generally requires the establishment of suitable models to simulate the emission behaviors. Existing models are mainly aimed at building materials and can be classified into an empirical model and mass transfer model [10,19]. Although the first type of model has simple form and is easy to use, the empirical parameters involved have no actual physical meaning, and rely heavily on the specific test conditions, which cannot be extended to other emission conditions. Therefore, the development of mass transfer model is particularly important. The multi-layer emission model can be applicable for multi-layer material structures [20]. However, the semi-analytical solution of this model is relatively complicated, which prevents its wide use in engineering applications.

There are three key parameters in the model, i.e., the initial emittable concentration (C_0), the diffusion coefficient (D_m), and the partition coefficient (K) [6,10,19]. Accurate determination of these parameters is the premise of using models for prediction. According to the definition of these key parameters, various methods have been proposed, such as the porosity method, twin-chamber method, C-history method, alternately airtight/ventilated emission method [11,21–27]. Most prior studies focus on the emissions of VOCs from building materials, while that of furniture has seldom been examined. Compared with building materials, the structure and emission mechanisms of entire furniture items are more complicated. Due to the difference in the small wood-based boards and real furniture, there is still a gap between the VOC emissions in chamber tests and that in realistic indoor settings.

As far as the ventilation strategies are concerned, much work targets at developing energy-efficient ventilation models [28]. For instance, Rackes et al. [29] proposed a multi-contaminant model for analyzing the impact of mechanical ventilation strategies on the indoor air quality of offices. Some studies focus on natural ventilation [30], hybrid ventilation [31], or mechanical ventilation [32]. There are also investigations focusing on developing ventilation optimization in the design phase [33,34]. However, less attention has been paid to the optimal control of ventilation over a long period. To achieve a healthy indoor environment with minimum energy consumption, it is necessary to simultaneously analyze the indoor air quality when considering ventilation, that is, by combining VOC emission characteristics and ventilation control strategies.

The mechanical ventilation system of office buildings often adopts intermittent operation mode. During the period when the ventilation system is closed, the VOC concentration increases. Especially for the newly renovated office, there is a potential threat to the health of the employee. How to determine the pre-ventilation time to ensure the safety of the indoor environment, during working hours, is an important issue needing to be considered.

The main purpose of this study is to examine the effect of an intermittent ventilation strategy on controlling formaldehyde concentrations in office rooms. A model predictive control (MPC) strategy is proposed for intermittent ventilation systems to achieve a healthy indoor environment. The strategy is based on a dynamic model for predicting VOC emissions. The three key parameters in the model are obtained by large-scale chamber experiments and an improved C-history method. Dynamic simulation based on the determined key parameters is then applied for a typical office room to analyze the control characteristics of an intermittent ventilation system. The influence of some major factors (i.e., vacant time of the room, loading ratio and air change rate) on the pre-ventilation time is analyzed and compared.

2. Methods

2.1. Model for Predicting VOC Emissions

To simplify the analysis of the problem for VOC emissions from material, the following assumptions are introduced: (1) the VOC concentration inside the material is uniform; (2) the initial VOC concentration in the chamber is zero; (3) the emission of VOCs from the material is one-dimensional; (4) the partition process at the material/air interface obeys Henry's law; (5) the inlet VOC concentration to the chamber or the room is zero.

Based on the above assumptions, the emission process of VOCs inside the furniture material follows Fick's law, which can be described by the one-dimensional diffusion equation [6]:

$$\frac{\partial C_m(x,t)}{\partial t} = D_m \frac{\partial^2 C_m(x,t)}{\partial x^2} \tag{1}$$

The initial condition and boundary conditions are:

$$C_m(x,0) = C_0 \tag{2}$$

$$-D_{\mathrm{m}}\frac{\partial C_{\mathrm{m}}(x,t)}{\partial x}\bigg|_{x=L} = h_{\mathrm{m}}(C_{\mathrm{s}}(t) - C_{\mathrm{a}}(t)) \tag{3}$$

$$\frac{\partial C_{\mathrm{m}}(x,t)}{\partial x}\bigg|_{x=0} = 0 \tag{4}$$

where, C_{m} is the VOC concentration in the furniture, μg/m^3; D_{m} is the diffusion coefficient of VOCs inside the material, m^2/s; C_0 is the initial emittable concentration, μg/m^3; x is the distance in the diffusion direction, m; t is the emission time, s; C_{a} is the gas-phase VOC concentration in the chamber or the room, μg/m^3; C_{s} is the VOC concentration in the air adjacent to the material surface, $C_{\mathrm{s}}(t) = C_{\mathrm{m}}(L,t)/K$, μg/m^3; L is the thickness of the material, m; K is the partition coefficient, dimensionless.

The above Equations (1)–(4) are not closed because of the existence of C_{a}. An equation containing C_{a} is given as follows based on mass balance of VOCs in the chamber or the room:

$$V_{\mathrm{r}}\frac{dC_{\mathrm{a}}(t)}{dt} = Fh_{\mathrm{m}}(C_{\mathrm{s}}(t) - C_{\mathrm{a}}(t)) - QC_{\mathrm{a}}(t) \tag{5}$$

with the initial condition

$$C_{\mathrm{a}}(t)|_{t=0} = C_{\mathrm{a},0} \tag{6}$$

where, V_{r} is volume of the room, m^3; Q is the ventilation rate, m^3/s; F is the effective emission area of the furniture material, m^2.

Now the system of Equations (1)–(6) is closed, and the VOC concentrations in the room air can be solved analytically (when Q is constant) or numerically (by finite difference method).

2.2. Improved C-History Method for Determining the Key Parameters

In this study, an improved C-history method [35] is applied to determine the three key parameters (C_0, D_{m}, K) of VOC emissions from furniture. The principle is briefly introduced here. By combining the above Equations (1)–(6), Yang et al. [35] derived an analytical solution to describe the VOC emissions under constant ventilation rate. This analytical solution is then simplified into the following form when the emission is in the mid-term stage:

$$\ln C_{\mathrm{a}}(t) = A \cdot t + B \tag{7}$$

$$A = -D_{\mathrm{m}}L^{-2}{q_1}^2 \tag{8}$$

$$B = \ln\left(2C_0\beta\frac{q_1 \sin q_1}{G_1}\right) \tag{9}$$

$$q_1 \tan q_1 = \frac{\alpha - q_1^2}{K\beta + (\alpha - q_1^2)KBi_{\mathrm{m}}^{-1}} \tag{10}$$

$$\begin{aligned} G_1 = \; & [K\beta + (\alpha - q_1^2)KBi_{\mathrm{m}}^{-1} + 2]q_1^2 \cos q_1 \\ & + [K\beta + (\alpha - 3q_1^2)KBi_{\mathrm{m}}^{-1} + \alpha - q_1^2]q_1 \sin q_1 \end{aligned} \tag{11}$$

where, A and B are the slope and intercept of Equation (7), respectively, which are functions of C_0, D_{m} and K, as is shown in Equations (8) and (9); q_1 is the first positive root of Equation (10) in the range of 0-π/2; $\beta = FL/V_{\mathrm{r}}$; $\alpha = QL^2/V_{\mathrm{r}}D_{\mathrm{m}}$; Bi_{m} (= $h_{\mathrm{m}}L/D_{\mathrm{m}}$) is the mass transfer Biot number; h_{m} is the convective mass transfer coefficient, m/s, which can be calculated by empirical correlations [36].

Thus, if the gas-phase VOC concentrations are treated as the form of the logarithm of excess concentration in Equation (7), A and B can be obtained by performing linear curve fitting with the experimental data. An initial value of K is estimated by correlations [37] and taken as known, then the parameters C_0 and D_{m} can be obtained by solving Equations (8) and (9).

2.3. Control Strategy for Intermittent Ventilation

An important criterion in intermittent ventilation control is to ensure indoor environment healthy with minimal energy consumption. Model predictive control (MPC) is considered to be one of the most effective strategies for achieving this goal [38]. The main difficulty in the application of model predictive control technology is the establishment of prediction models, which can be divided into physical models [39,40], data models (also known as black box models) [41,42], and semi-physical models [43]. Generally, the detailed and complex physical models are mainly appropriate for the simulation of control characteristics of the system, while the simplified semi-physical models or black box models are suitable for the development research of the controllers. This study proposes to use the VOC prediction model (solve Equations (1)–(6) numerically in Section 2.1) that takes into account the physical transport of VOCs from the furniture, for studying the ventilation control strategy.

The objective of the intermittent ventilation control strategy is to reduce the runtime of the system while maintaining a healthy indoor environment during working hours. The ventilation system uses its maximum capacity for the initial pre-ventilation stage. Once the VOC concentration is reduced to below the healthy limited value, the system adjusts the rate of ventilation to meet the air volume requirements for normal air conditioning operation. The curve of indoor VOC concentration on a typical working day for this control strategy is shown in Figure 1. The pre-ventilation time in Figure 1 denotes the time that the intermittent ventilation system needs to run in advance before the staff's working hours.

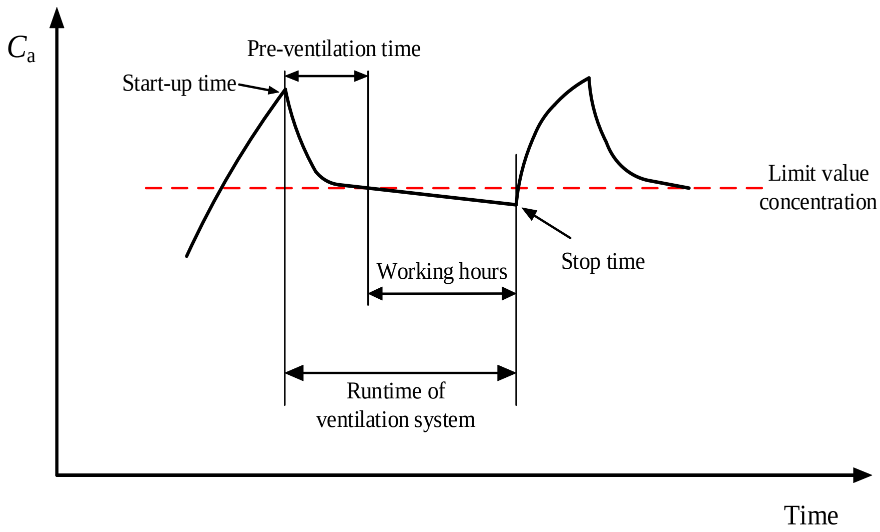

Figure 1. Schematic of VOC concentration variations in the office room under intermittent ventilation.

Based on the key parameters obtained from experiments, the physical model described in Section 2.1 and the control strategy shown in Figure 1, the following optimization problem is proposed:

Known: office room and VOC source information, including the structural sizes of the furniture and the key parameters of VOC emission from the furniture, which can be measured by the large-scale chamber experiments and the improved C-history method, as well as field investigations of office rooms.

Unknown: start schedule of the ventilation system, indoor VOC concentration.

Objective: minimize the runtime of the ventilation system.

Constraint conditions: indoor gas-phase VOC concentration is lower than the limit of the healthy level (less than 0.1 mg/m^3 for formaldehyde) during working hours (9:00–17:00).

It should be noted that the analytical solution derived in Section 2.2, requires a basic assumption of constant ventilation rate. However, in the study of control strategy for intermittent ventilation, the ventilation rate is a dynamic parameter. Therefore, the analytical solution and the linear regression method (improved C-history method) is used for determining the key parameters in Section 2.2. Compared with the nonlinear fitting technique, the linear fitting in the C-history method can escape the problem of multiple solutions, thus is applied in the present study. In Section 2.3, numerical solutions are used by finite difference method to examine the effect of ventilation strategy.

3. Experiments and Simulation Cases

3.1. Experimental System

A schematic diagram of the experimental system for measuring the three key parameters based on the improved C-history method is shown in Figure 2. The experimental system consists of three parts, as follows: a ventilation system, a temperature and humidity-controlled chamber, and a sampling system. The ambient air was purified, and then introduced into the chamber. We measured the background concentrations of targeted VOCs in the chamber before the tests, and the background concentration levels met the requirements of ASTM Standard D6670 [44]. The 0.5 m^3 stainless-steel chamber was equipped with a fan to ensure the air was well mixed, with mixing degree greater than 90% obtained from the test [44]. The chamber experiments were performed at controlled temperature (24 $\pm$ 0.5 °C), relatively humidity (50 $\pm$ 5%), and air change rate (0.5 h^{-1}). The tested panel furniture (Figure 3; area: 1.46 m^2; thickness: 20 mm; double surface emission) was put in the chamber to emit freely to reach the equilibrium. Formaldehyde was selected as the target pollutant, due to its high health risk and concern. The gas-phase formaldehyde concentrations were sampled at the outlet of the chamber with a photoacoustic gas monitor, INNOVA-1412i, and the total experimental time was 150 h. Before the experiment, the INNOVA-1412i was calibrated with high performance liquid chromatography (HPLC) for formaldehyde measurement.

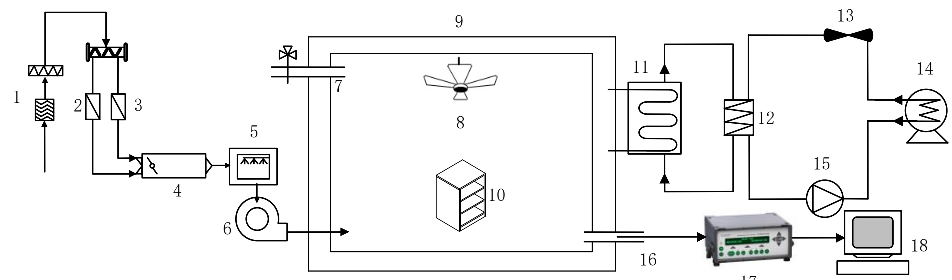

Figure 2. Schematic of the VOC emission testing system. 1-purification module; 2-heating coil; 3-cooling coil; 4-mixed box; 5-humidifier; 6-ventilator; 7-air outlet; 8-fan; 9-environmental chamber; 10- furniture; 11-heat exchanger; 12-evaporator; 13-throttle valve; 14-condenser; 15-compressor; 16-sample connection; 17-INNOVA-1412i; 18-processor.

Figure 3. Tested panel furniture for the VOC emissions.

3.2. Office and VOC Source Description

The size of the studied office room is 5 m × 4 m × 3 m. The layout of the room is shown in Figure 4. The sources of VOC emissions in the room are desks (panel furniture). The structural sizes of the desks are: length, 1700 mm; width, 900 mm; height, 750 mm; thickness, 20 mm.

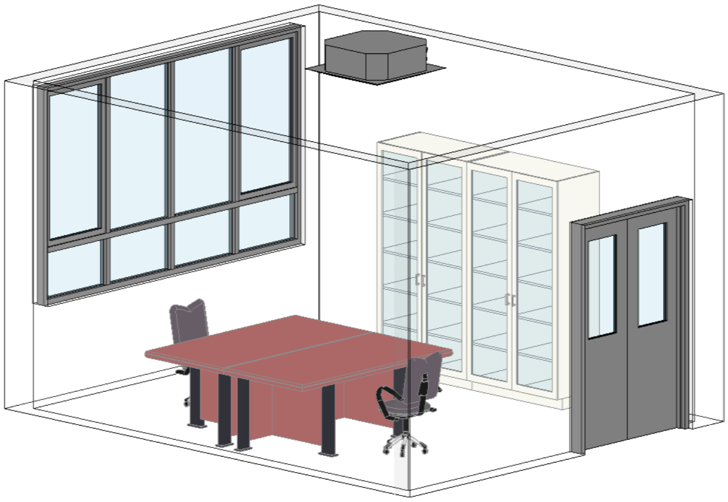

Figure 4. The layout of the studied office room.

3.3. Ventilation Scenarios and Simulation Cases

The setting of ventilation scenarios is divided into two stages. Stage I: after the new desks (panel furniture) are put in, the office room is kept vacant for a period of time (defined as the vacant time), and the VOC concentration is diluted by natural ventilation. Figure 5 gives the relationship between the air change rate and window opening degree. The variations of the air change rate, at a certain window opening degree, are due to the dynamic external meteorological conditions (e.g., variable wind speed). In this study, the window opening degree of 25% is selected, with an air change rate of the room about 5 h^{-1}. Stage II: after the office is normally running, the intermittent mechanical ventilation is carried out according to the control strategy described in Section 2.3.

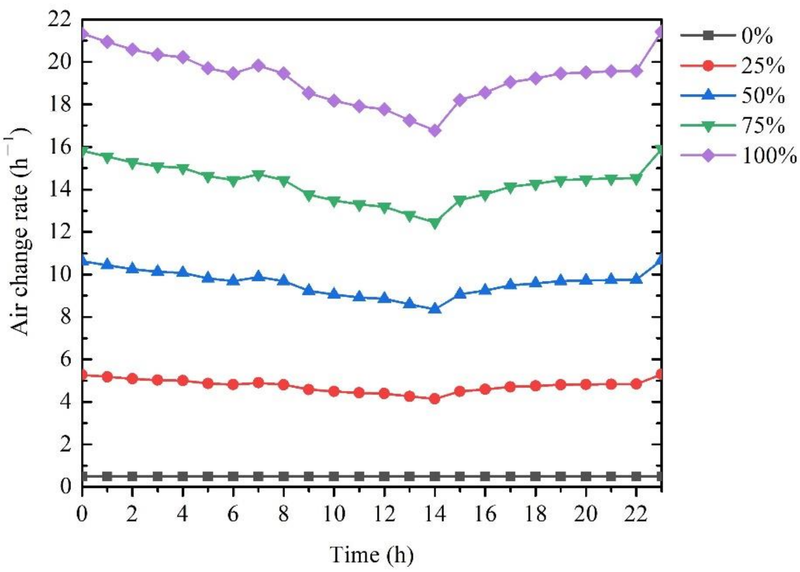

Figure 5. Relationship between the air change rate and window opening degree during the natural ventilation scenario.

For the purpose of analyzing the impact of the main factors (i.e., the vacant time, loading ratio, and air change rate) on the pre-ventilation time, simulations are performed for four groups of cases as summarized in Table 1. Among them, cases II-A to II-C use the standard case I-A as reference.

Table 1. Simulation cases.

Cases	Vacant Time of the Room (day)	Furniture Loading Ratio (m^2/m^3)	Air Change Rate during Pre-Ventilation (h^{-1})
I-A	80	0.30	1
II-A	80–100	0.30	1
II-B	80	0.17–0.30	1
II-C	80	0.30	1–12

4. Results and Discussion

4.1. Measurement of the Key Parameters

By performing chamber experiments on the panel furniture, the gas-phase formaldehyde concentrations were measured at regular intervals for about 150 h. The experimental data at typical time points during the emission period (30 h, 48 h, 54 h, 72 h, 78 h, 96 h) are selected for analysis with the improved C-history method. Figure 6 shows the linear curve fitting results by applying Equation (7) to treat the experimental data. The square of correlation coefficient (R^2) is 0.98, implying high regression accuracy. Based on the slope (A) and intercept (B) of the regression line and a pre-determined K (obtained by correlations in Yang et al.'s study [37]), the two key parameters C_0 and D_m can be determined by solving Equations (8) and (9). The obtained key parameters of formaldehyde emission from the tested panel furniture are: K = 3289; C_0 = 2.07 × 10^5 μg/m^3; D_m = 1.18 × 10^{-10} m^2/s.

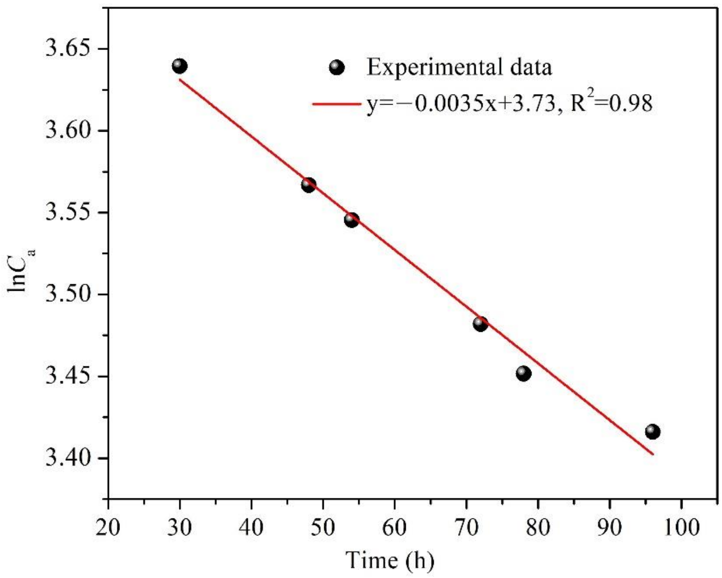

Figure 6. Linear curve fitting results by applying Equation (7) to treat the experimental data.

According to the survey, the selected panel furniture is one of the most common and major VOC emission sources in Chinese offices. In addition, the emissions of VOCs from furniture have also been conducted in prior chamber studies [11,45,46]. By comparison, the determined key parameters in this study are within the range of previous results (C_0 in 10^4–10^8 μg/m^3, D_m in 10^{-11}–10^{-8} m^2/s, K in 10^2–10^4). Additionally, the gas-phase formaldehyde concentrations also change similarly with that in a prior study [47]. The above analysis implies that although just one kind of panel furniture is tested, the present study can still be regarded as representative.

4.2. Validation of the Measured Key Parameters

The measured C_0, D_m and K are substituted into an analytical solution [48] to calculate the gas-phase formaldehyde concentration in the chamber, and these results are then compared with the experimental data during the whole time, to evaluate the effectiveness of the method.

The analytical solution derived by Xu and Zhang [48] is as follows:

$$C_m(x,t) = KC_a(t) + \sum_{n=1}^{\infty} \frac{\sin(\beta_n L)}{\gamma_n} \frac{2(\gamma_n{}^2+H^2)}{L(\gamma_n{}^2+H^2)+H} \cos(\gamma_n x) \times \left[(C_0 - KC_a(0))e^{-D_m\gamma_n^2 t} + \int_0^t e^{-D_m\gamma_n^2(t-\tau)} KdC_a(\tau)\right] \quad (12)$$

where, $H = h_m/KD_m$, γ_n (n = 1, 2, ...) are the positive roofs of

$$\gamma_n \tan(\gamma_n L) = H \quad (13)$$

The gas-phase VOC concentration $C_a(t)$ can be calculated by combining these two equations and the mass balance, Equation (5).

Figure 7 shows the comparison between the model prediction and experimental data. The figure reveals that most of the experimental data are located in the emission curve predicted by the analytical model. The performance of the model is evaluated by four statistical parameters recommended by the ASTM Standard D5157 [49], i.e., the correlation coefficient (R), the normalized mean square error (NMSE), the fractional bias (FB), and a similar index of bias (FS). The evaluation results listed in Table 2 demonstrate the effectiveness of the measurement method. It is also demonstrated that the improved C-history method, which is proposed for small chamber tests, can be extended to the key parameter measurement of furniture emissions in the large-scale chamber.

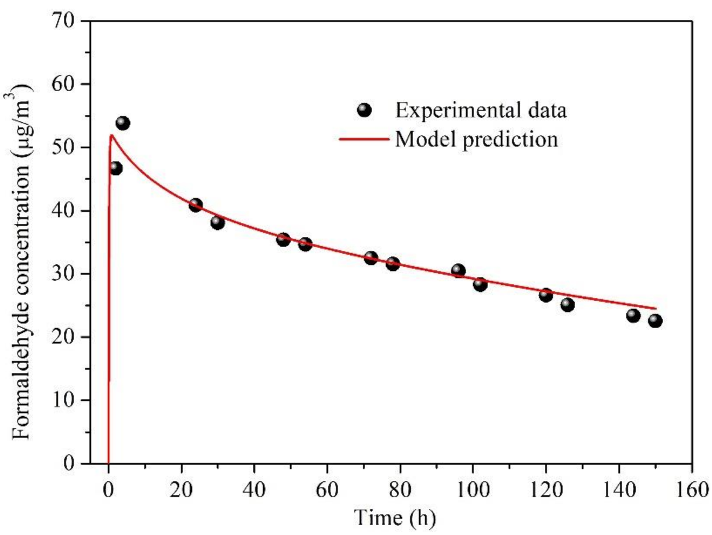

Figure 7. Comparison between the model prediction and experimental data.

Table 2. Model performance evaluation results.

	R^2	NMSE	FB	FS
Results in this study	0.95	0.0032	0.0159	−0.1255
Values of indicative of adequate model performance [49]	≥0.81	≤0.25	≤0.25	≤0.5

According to the principle of the improved C-history method, just the experimental data in the mid-term emission stage can be used for data fitting. Therefore, in Figure 6, just the experimental data during this stage (6 points) are used to perform the linear curve fitting, which are then used to determine the key parameters in the formaldehyde emission model. Figure 7 is used for validating the determined parameters. So, all the data are plotted in Figure 7. Since the data for validation are more than the data for deriving the key parameters, the good agreement between model predictions and all the experimental data in Figure 7 convincingly demonstrates the effectiveness of the measurement method and the model.

4.3. Formaldehyde Concentration Variation and Pre-Ventilation Time

For simulation case I-A, based on the intermittent ventilation control strategy and VOC emission model, the formaldehyde concentration variation is predicted during four weeks after the office is normally occupied. The results are shown in Figures 8–10.

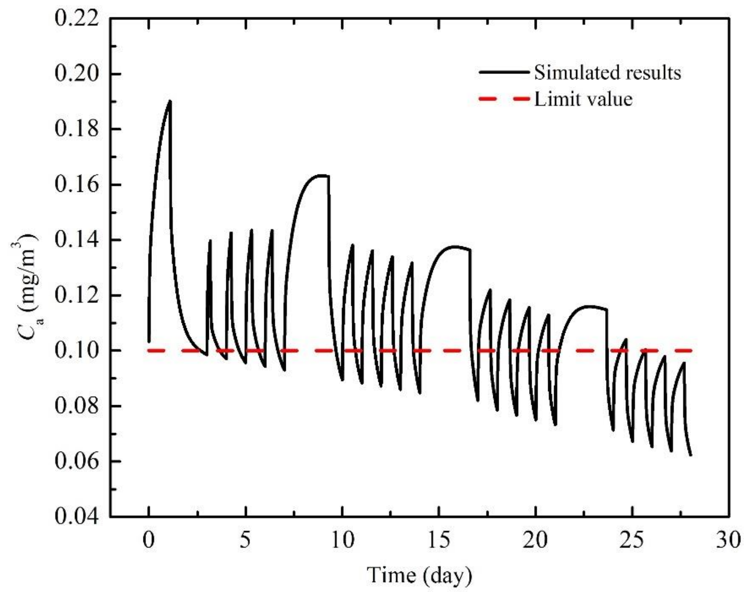

Figure 8. Formaldehyde concentration variations under intermittent ventilation.

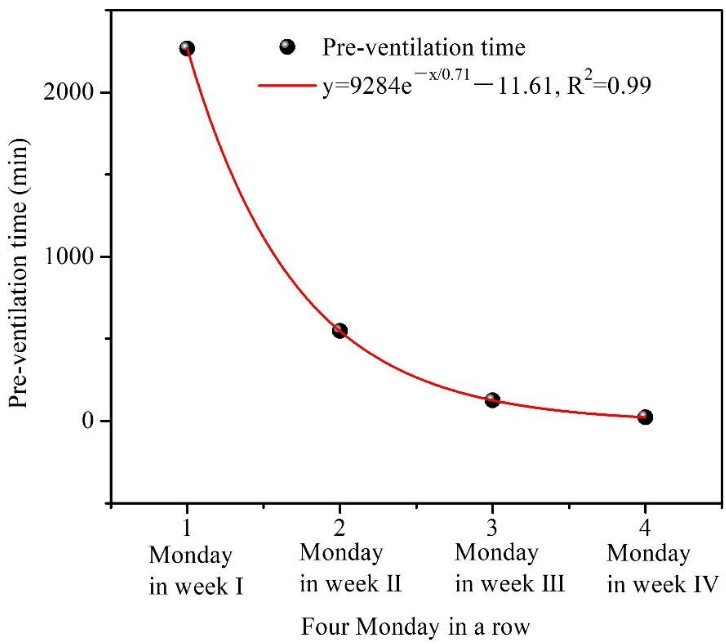

Figure 9. Pre-ventilation time for four consecutive Mondays.

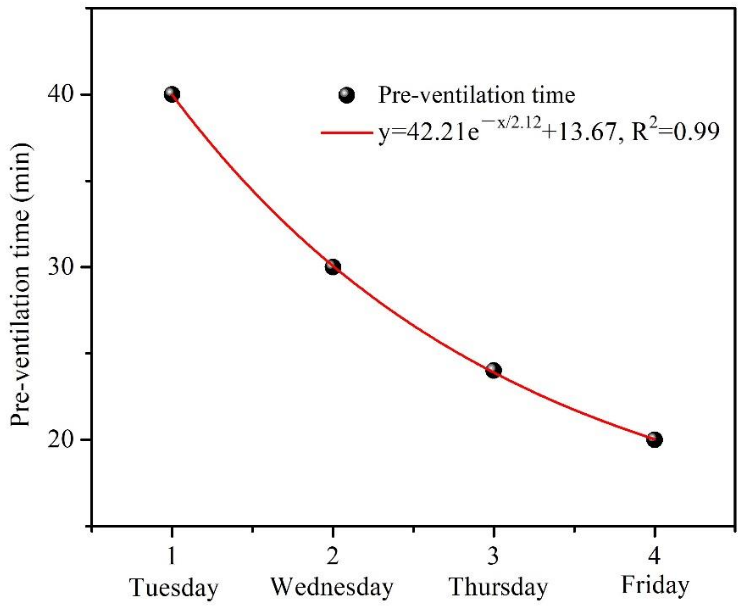

Figure 10. Pre-ventilation time from Tuesday to Friday in Week III.

Figure 8 shows that the indoor formaldehyde concentrations gradually decrease after the ventilation system is opened, and gradually increase when the ventilation system is stopped. The peak concentration gradually decreases with the time. Correspondingly, the time required for pre-ventilation gradually reduces. Figure 8 also represents that the indoor formaldehyde concentrations during working hours are effectively controlled below the limit value regulated by WHO guidelines (0.1 mg/m^3), even though the indoor formaldehyde concentrations will exceed the limit value for some times during the unoccupied period. A recent study [50] also indicated that the indoor VOC concentrations increased when the ventilation system was off and decreased when the ventilation system was on. This change pattern occurs in several cycles, which is consistent with the results in the present study (as Figure 8 shows).

Figure 9 reveals that, for the four consecutive weeks, the pre-ventilation time on Mondays shows a trend of exponential decay, from 2268 min on Monday of week I to 22 min on Monday of week IV. For the same week, the pre-ventilation time on Monday is obviously larger than that on other days, e.g., the pre-ventilation time is 126 min on Monday of week III, and the time is decreased to 40 min on Tuesday of the same week. The pre-ventilation time from Tuesday (40 min) to Friday (20 min) also shows an exponential decay, as indicated in Figure 10. In this figure, the x-axis represents four consecutive working days (from Tuesday to Friday) in week III. Numbers 1–4 correspond to these four days, respectively, and are used for the formula fitting.

4.4. Impact Factor Analysis on the Pre-Ventilation Time

In order to analyze the influence of different factors on the duration of pre-ventilation, the pre-ventilation time on Tuesday of the first week after the vacant period of the office room, is analyzed under different simulated cases (II-A to II-C).

(1) Vacant time of the office room

Figure 11 shows that the time required for pre-ventilation decreases exponentially (from 848 min to 0 min), as the vacant time of the office room increases (from 80 days to 100 days). In particular, under the simulated condition of case II-A, when the room is kept vacant and maintains proper ventilation for up to 100 days after the new desks are put in, the required pre-ventilation time approaches zero. When the loading ratio of the furniture is 0.30 m^2/m^3 and the natural air change rate is 5 h^{-1}, the required vacant time is at least 80 days.

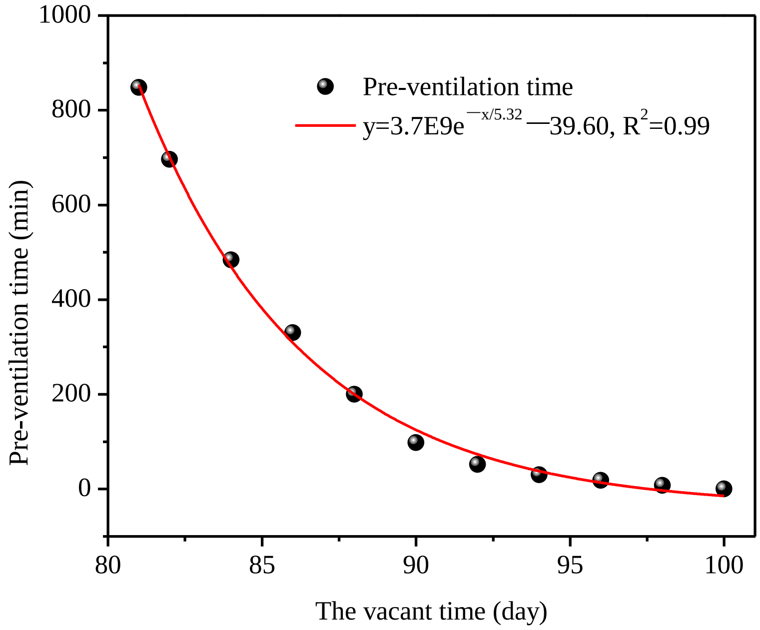

Figure 11. The relationship between the pre-ventilation time and the vacant time.

(2) Furniture loading ratio

The furniture loading ratio is defined as the ratio of furniture's VOC effective emission area to the room volume, namely A/V (m^2/m^3). The furniture loading ratio has a great impact on the formaldehyde concentration as well as the pre-ventilation time. The simulation results of cases II-B show that, when the loading ratio increases from 0.17 to 0.30, the pre-ventilation time for the first Tuesday increases from 4 min to 848 min. Figure 12 indicates that, the pre-ventilation time increases exponentially with the increase in the furniture loading ratio.

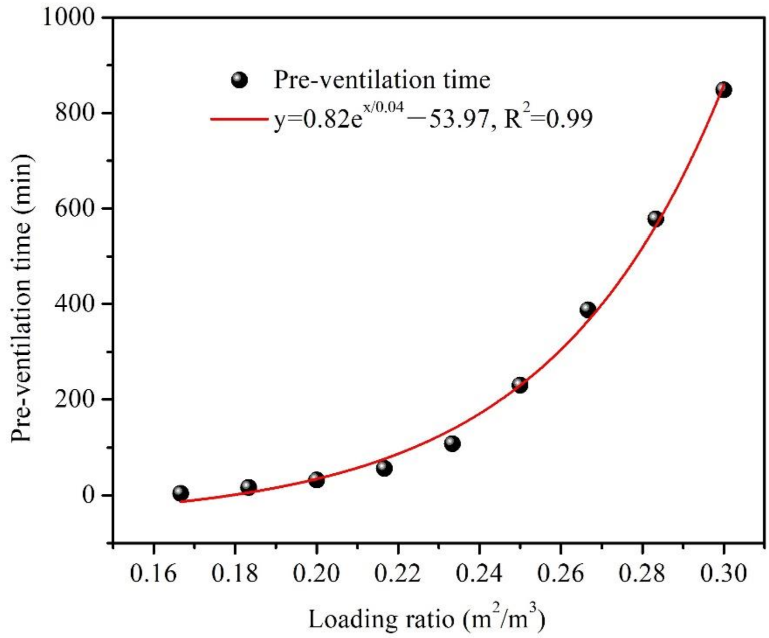

Figure 12. The relationship between the pre-ventilation time and the loading ratio.

(3) Air change rate

Ventilation equipment with larger capacity is helpful for ensuring that the formaldehyde concentration in the room is diluted to the healthy limited value faster. The simulation results of cases II-C indicate that, when the air change rate increases to a certain extent (e.g., more than 2 h^{-1}), the pre-ventilation time will not decrease significantly by increasing the air change rate, as shown in Figure 13. The reason lies in that, when the air change rate is large enough, the indoor formaldehyde concentration can be controlled below the health limit value in a short time (e.g., 30 min), and the space for the pre-ventilation time continuing to reduce is limited. For example, the pre-ventilation time reduces from 30 min to 10 min when the air change rate increases from 2 h^{-1} to 4 h^{-1}. However, the energy consumption and initial investment for the ventilation system will increase obviously by increasing the ventilation rate. This means an air change rate of 2 h^{-1} is the most appropriate choice for ventilation for the cases studied (cases II-C). It should be noted that, the optimal ventilation rate for pre-ventilation is related to the VOC emission characteristics of indoor furniture and needs to be obtained according to the analysis of different scenarios.

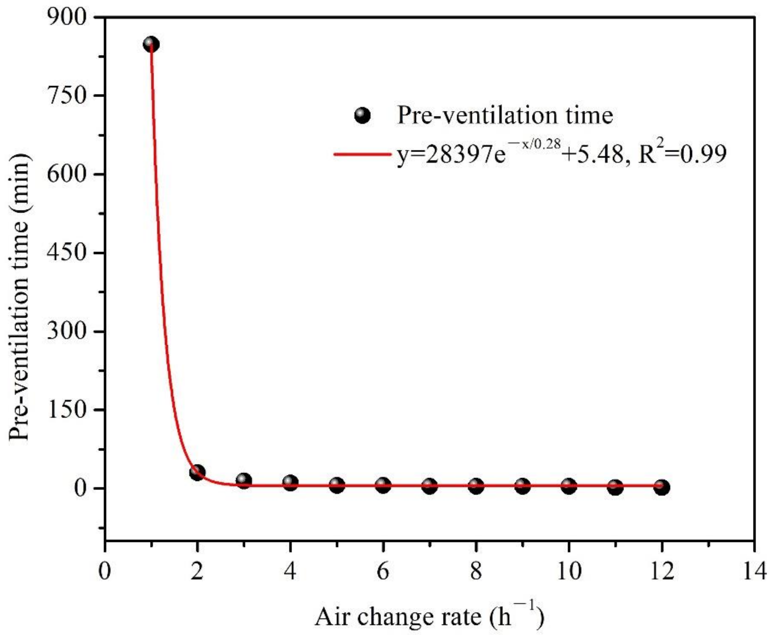

Figure 13. The relationship between the pre-ventilation time and the air change rate.

5. Conclusions

Based on the experiments on the emission characteristics of panel furniture and the model for predicting formaldehyde emissions, this study explored the intermittent ventilation strategy for the typical office room, to ensure a healthy indoor environment for employees during working hours. By virtue of the dynamic simulation of formaldehyde concentrations in an office room, the influences of some main factors (including the vacant time of the office room, the furniture loading ratio, and the air change rate) on the pre-ventilation time are analyzed. The main conclusions are as follows:

(1) The good agreement between the model prediction and experimental data demonstrates that the improved C-history method, which is proposed for measuring the key parameters of building materials in small-scale chambers, can be extended to be applicable for measurement of the furniture's VOC emissions in large-scale chamber.

(2) The key point of the intermittent ventilation strategy is to predict the pre-ventilation time for each working day based on VOC prediction model. The pre-ventilation time of the intermittent ventilation system ranges from several minutes to several hours.

(3) Under a certain furniture loading ratio (0.30 m^2/m^3) and air change rate (1 h^{-1}), the pre-ventilation time owns an exponential relationship with the vacant time. For example,

the time required for pre-ventilation on Tuesday of the first week declines exponentially (from 848 min to 0 min) as the vacant duration increases (from 80 to 100 days).

(4) Under a certain vacant time (80 days) and air change rate (1 h^{-1}), the pre-ventilation time increases (from 4 min to 848 min) exponentially with the increase in furniture loading ratio (from 0.17 to 0.30 m^2/m^3).

(5) Under a certain furniture loading ratio (0.30 m^2/m^3) and vacant time (80 days), the pre-ventilation time decreases exponentially with the increase in the air change rate. However, when the air change rate increases to a certain extent (e.g., more than 2 h^{-1}), the pre-ventilation time will not decrease significantly by increasing the ventilation rate.

The conclusions are dependent on the selected typical modelling conditions. Since the effectiveness of the measurement method and the model are demonstrated through experiments, it should be very helpful for analyzing other scenarios by virtue of the proposed method.

Author Contributions: Conceptualization, J.X.; Data curation, L.H.; Formal analysis, Y.L.; Investigation, B.X. and Y.D.; Methodology, B.X., Y.L. and J.X.; Validation, Y.D.; Writing—original draft, B.X.; Writing—review & editing, X.W. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52178062) and the Fundamental Research Funds for the Central Universities (2018 MS023).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Engelmann, W.H. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *J. Expo. Sci. Environ. Epidemiol.* **2001**, *11*, 231–252. [CrossRef]
2. WHO. Indoor Air Pollutants: Exposure and Health Effects. In *EURO Reports and Studies 78*; World Health Organization: Geneva, Switzerland, 1983.
3. Baudet, A.; Baurès, E.; Guegan, H.; Blanchard, O.; Guillaso, M.; Le Cann, P.; Gangneux, J.P.; Florentin, A. Indoor air quality in healthcare and care facilities: Chemical pollutants and microbiological contaminants. *Atmosphere* **2012**, *12*, 1337. [CrossRef]
4. Landrigan, P.J.; Fuller, R.; Acosta, N.J.R.; Adeyi, O.; Arnold, R.; Basu, N.; Baldé, A.B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J.I.; et al. The Lancet Commission on pollution and health. *Lancet* **2018**, *391*, 462–512. [CrossRef]
5. Zhang, H.; Chen, F.; Zheng, L. The whole process control strategy and case analysis of indoor air quality in office building decoration engineering. *J. Green Build.* **2020**, *12*, 89–92.
6. Little, J.C.; Hodgson, A.T.; Gadgil, A.J. Modeling emissions of volatile organic compounds from new carpets. *Atmos. Environ.* **1994**, *28*, 227–234. [CrossRef]
7. Salthammer, T.; Mentese, S.; Marutzky, R. Formaldehyde in the indoor environment. *Chem. Rev.* **2010**, *110*, 2536–2572. [CrossRef]
8. Zhang, R.; Tan, Y.; Wang, Y.; Wang, H.; Zhang, M.; Liu, J.; Xiong, J. Predicting the concentrations of VOCs in a controlled chamber and an occupied classroom via a deep learning approach. *Build. Environ.* **2022**, *207*, 108525. [CrossRef]
9. Hu, K.; Chen, Q. Ventilation optimization for reduction of indoor semi-volatile organic compound concentration based on the variational principle. *Build. Environ.* **2015**, *94*, 676–682. [CrossRef]
10. Zhang, Y.; Xiong, J.; Mo, J.; Gong, M.; Cao, J. Understanding and controlling airborne organic compounds in the indoor environment: Mass-transfer analysis and applications. *Indoor Air* **2016**, *26*, 39–60. [CrossRef]
11. Wang, Y.; Wang, H.; Tan, Y.; Liu, J.; Wang, K.; Ji, W.; Sun, L.; Yu, X.; Zhao, J.; Xu, B.; et al. Measurement of the key parameters of VOC emissions from wooden furniture, and the impact of temperature. *Atmos. Environ.* **2021**, *259*, 118510. [CrossRef]
12. Sundell, J.; Levin, H.; Nazaroff, W.W.; Cain, W.S.; Fisk, W.J.; Grimsrud, D.T.; Gyntelberg, F.; Li, Y.; Persily, A.K.; Pickering, A.C.; et al. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air* **2011**, *21*, 191–204. [CrossRef] [PubMed]
13. Feng, G.; Jiang, B.; Huang, K.; Yu, S. Study on distribution law of indoor formaldehyde concentration under natural ventilation condition in severe cold area. *Procedia Eng.* **2017**, *20*, 724–729. [CrossRef]
14. Pamonpol, K.; Areerob, T.; Prueksakorn, K. Indoor air quality improvement by simple ventilated practice and sansevieria trifasciata. *Atmosphere* **2020**, *11*, 271. [CrossRef]
15. Nazaroff, W.W. Residential air-change rates: A critical review. *Indoor Air* **2021**, *31*, 282–313. [CrossRef]
16. Tian, E.; Xia, F.; Wu, J.; Zhang, Y.; Li, J.; Wang, H.; Mo, J. Electrostatic air filtration by multifunctional dielectric hetero-caking filters with ultra-low pressure drop. *ACS Appl. Mater. Interfaces* **2020**, *12*, 29383–29392.

17. Tian, E.; Yu, Q.; Gao, Y.; Wang, H.; Wang, C.; Zhang, Y.; Li, B.; Zhu, M.; Mo, J.; Xu, G.; et al. Ultralow resistance two-stage electrostatically assisted air filtration by polydopamine coated PET coarse filter. *Small* **2021**, *17*, 2102051. [CrossRef]
18. Xiao, R.; Mo, J.; Zhang, Y.; Gao, D. An in-situ thermally regenerated air purifier for indoor formaldehyde removal. *Indoor Air* **2018**, *28*, 266–275. [CrossRef]
19. Liu, Z.; Ye, W.; Little, J.C. Predicting emissions of volatile and semivolatile organic compounds from building materials: A review. *Build. Environ.* **2013**, *64*, 7–25. [CrossRef]
20. Hu, H.; Zhang, Y.; Wang, X.; Little, J.C. An analytical mass transfer model for predicting VOC emissions from multi-layered building materials with convective surfaces on both sides. *Int. J. Heat Mass Transf.* **2007**, *50*, 2069–2077. [CrossRef]
21. Haghighat, F.; Lee, C.S.; Ghaly, W.S. Measurement of diffusion coefficient of VOCs for building materials: Review and development of a calculation procedure. *Indoor Air* **2002**, *12*, 81–91. [CrossRef]
22. Blondeau, P.; Tiffonnet, A.L.; Damian, A.; Amiri, O.; Molina, J.L. Assessment of contaminant diffusivities in building materials from porosimetry tests. *Indoor Air* **2003**, *13*, 310–318. [CrossRef]
23. Meininghaus, R.; Gunnarsen, L.; Knudsen, H.N. Diffusion and sorption of volatile organic compounds in building materials-impact on indoor air quality. *Environ. Sci. Technol.* **2000**, *34*, 3101–3108. [CrossRef]
24. Xiong, J.; Yao, Y.; Zhang, Y. C-history method: Rapid measurement of the initial emittable concentration, diffusion and partition coefficients for formaldehyde and VOCs in building materials. *Environ. Sci. Technol.* **2011**, *45*, 3584–3590. [CrossRef] [PubMed]
25. Huang, S.; Xiong, J.; Zhang, Y. A rapid and accurate method, ventilated chamber C-history method, of measuring the emission characteristic parameters of formaldehyde/VOCs in building materials. *J. Hazard. Mater.* **2013**, *261*, 542–549. [CrossRef]
26. Zhou, X.; Liu, Y.; Liu, J. Alternately airtight/ventilated emission method: A universal experimental method for determining the VOC emission characteristic parameters of building materials. *Build. Environ.* **2018**, *130*, 179–189. [CrossRef]
27. Zhang, M.; Xiong, J.; Liu, Y.; Misztal, P.K.; Goldstein, A.H. Physical-chemical coupling model for characterizing the reaction of ozone with squalene in realistic indoor environments. *Environ. Sci. Technol.* **2021**, *55*, 1690–1698. [CrossRef]
28. Chenari, B.; Carrilho, J.D.; Silva, M.G. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1426–1447. [CrossRef]
29. Rackes, A.; Waring, M.S. Modeling impacts of dynamic ventilation strategies on indoor air quality of offices in six US cities. *Build. Environ.* **2013**, *60*, 243–253. [CrossRef]
30. Kleiven, T. Natural Ventilation in Buildings: Architectural Concepts, Consequences and Possibilities. Ph.D. Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2003.
31. Turner, W.J.N.; Walker, I.S. Using a ventilation controller to optimize residential passive ventilation for energy and indoor air quality. *Build. Environ.* **2013**, *70*, 20–30. [CrossRef]
32. Awbi, H.B. Ventilation for good indoor air quality and energy efficiency. *Energy Procedia* **2017**, *112*, 277–286. [CrossRef]
33. Laverge, J.; Janssens, A. Optimization of design flow rates and component sizing for residential ventilation. *Build. Environ.* **2013**, *65*, 81–89. [CrossRef]
34. Ai, Z.T.; Mak, C.M. Short-term mechanical ventilation of air-conditioned residential buildings: A general design framework and guidelines. *Build. Environ.* **2016**, *108*, 12–22. [CrossRef]
35. Yang, T.; Zhang, P.; Xu, B.; Xiong, J. Predicting VOC emissions from materials in vehicle cabins: Determination of the key parameters and the influence of environmental factors. *Int. J. Heat Mass Transf.* **2017**, *110*, 671–679. [CrossRef]
36. Bejan, A. *Convective Heat Transfer*; John Wiley & Sons Inc.: New York, NY, USA, 1995.
37. Yang, X.; Chen, Q.; Zhang, J.S.; Magee, R.; Zeng, J.; Shaw, C.Y. Numerical simulation of VOC emissions from dry materials. *Build. Environ.* **2001**, *36*, 1099–1107. [CrossRef]
38. Afram, A.; Janabi-Sharifi, F. Theory and applications of HVAC control systems—A review of model predictive control (MPC). *Build. Environ.* **2014**, *72*, 343–355. [CrossRef]
39. Wemhoff, A.P.; Frank, M.V. Predictions of energy savings in HVAC systems by lumped models. *Energy Build.* **2010**, *42*, 1807–1814. [CrossRef]
40. Vasak, M.; Starcic, A.; Martincevic, A. Model predictive control of heating and cooling in a family house. In Proceedings of the 34th International Convention MIPRO, Opatija, Croatia, 23–27 May 2011; pp. 739–743.
41. Chen, J.; Lian, Z.; Tan, L.; Zhu, W.; Zhang, W. Modeling and experimental research on ground-source heat pump in operation by neural network. In Proceedings of the International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, Changsha, China, 19–20 February 2011; pp. 459–462.
42. Homod, R.Z.; Sahari, K.S.M.; Almurib, H.A.; Nagi, F.H. Fuzzy model identification of indoor thermal comfort based on PMV/PPD. *Build. Environ.* **2012**, *49*, 141–153. [CrossRef]
43. Lehmann, B.; Gyalistras, D.; Gwerder, M.; Wirth, K.; Carl, S. Intermediate complexity model for model predictive control of integrated room automation. *Energy Build.* **2013**, *58*, 250–262. [CrossRef]
44. ASTM D6670. *Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products*; ASTM International: West Conshohocken, PA, USA, 2018.
45. Xiong, J.; Chen, F.; Sun, L.; Yu, X.; Zhao, J.; Hu, Y.; Wang, Y. Characterization of VOC emissions from composite wood furniture: Parameter determination and simplified model. *Build. Environ.* **2019**, *161*, 106237. [CrossRef]

46. Zhang, X.; Wang, H.; Xu, B.; Wang, H.; Wang, Y.; Yang, T.; Tan, Y.; Xiong, J.; Liu, X. Predicting the emissions of VOCs/SVOCs in source and sink materials: Development of analytical model and determination of the key parameters. *Environ. Int.* **2022**, *160*, 107064. [CrossRef]
47. Liu, X.; Mason, M.A.; Guo, Z.; Krebs, K.A.; Roache, N.F. Source emission and model evaluation of formaldehyde from composite and solid wood furniture in a full-scale chamber. *Atmos. Environ.* **2015**, *122*, 561–568. [CrossRef]
48. Xu, Y.; Zhang, Y. An improved mass transfer based model for analyzing VOC emissions from building materials. *Atmos. Environ.* **2003**, *37*, 2497–2505. [CrossRef]
49. ASTM D5157. *Standard Guide for Statistical Evaluation of Indoor Air Quality Models*; ASTM International: West Conshohocken, PA, USA, 2019.
50. Wang, C.; Collins, D.B.; Arata, C.; Goldstein, A.H.; Mattila, J.M.; Farmer, D.K.; Ampollini, L.; DeCarlo, P.F.; Novoselac, A.; Vance, M.E.; et al. Surface reservoirs dominate dynamic gas-surface partitioning of many indoor air constituents. *Sci. Adv.* **2020**, *6*, eaay8973. [CrossRef] [PubMed]