Experimental evaluation of impact factors on VOC emissions from different building materials

Zhu Cheng
Sichuan University
Moxin Wang
Sichuan University
Nuoa Lei
Northwestern University
Ziyun Wang (wzyfirst@scu.edu.cn)
Sichuan University https://orcid.org/0000-0002-3283-1525
Jie Xiong
Chongqing University

Research Article

Keywords: building materials, TVOC, emission rate, environmental conditions, experimental study

Posted Date: March 24th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1406976/v1

Experimental evaluation of impact factors on VOC emissions from different building materials

Zhu Cheng[a], Moxin Wang[a], Nuoa Lei[b], Ziyun Wang[a]*, Jie Xiong[c]

[a]*MOE Key Laboratory of Deep Earth Science and Engineering, College of Architecture and Environment, Sichuan University, Chengdu 610065, China*

[b]*Department of Mechanical Engineering, Northwestern University, Illinois, United States*

[c]*Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China*

**Corresponding email: wzyfirst@163.com*

Abstract: With the continuing urbanization, much public attention has been placed on the pollutant emission of building materials. In this paper, experimental analysis of different emission rate impact factors (including temperature, relative humidity, ventilation, and seasonality) was performed to investigate the characteristic of formaldehyde and TVOC emissions from dry and wet building materials. The experiment was conducted in an environmental chamber, and the effects of the impact factors were analyzed using one-factor-at-a-time control method. The results showed that the VOC emission trends of dry and wet building materials are basically the same over time, so are the emission trend under different air exchange rates. Increased air exchange rate can promote the emission rate, for which the effect of air exchange rate is higher for the TVOC emission rate than for the formaldehyde emission rate. On the other hand, temperature and relative humidity showed significantly higher impacts for the emission rate of formaldehyde than the air exchange rate, and synergy between high temperature and high humidity could increase the emission rate of TVOC. Furthermore, it was found that the formaldehyde emission in the summer is much higher than that in the winter and transition season. In general, results of this research could provide invaluable data support and guidance for TVOC emission control, indoor air pollutants management, and control strategy optimization.

Key words: building materials, TVOC, emission rate, environmental conditions, experimental study

1.Introduction

The volatile organic compounds (VOCs) and formaldehyde are common indoor air pollutants that could give rise to poor indoor air quality (Amoatey et al. 2018; Mentese et al. 2010). Building materials have been recognized as the primary source of indoor air pollutants that are harmful for human health (Hodgson et al. 2002). Based on the internal structure of the material, building materials can be divided into dry materials and wet materials. Dry building materials are mainly porous media, including furniture, blockboard and wood products. And the VOCs emission process of the dry building material involves two parts, including inside diffusion and surface convection. As for wet materials (e.g., water-based paints or wood stain), surface convection usually dominates the emission processes, but the internal diffusion effect is determined by different situations (Spark et al. 1996; Tichenor et al. 1993). VOCs and formaldehyde emitted from building materials could lead to severe adverse health effects, such as asthmatic diseases (Billionnet et al. 2011), eye/nose irritation (Main et al. 1983; Lang et al. 2008) and allergy (Pibiri et al. 2020). Thus, understanding the effect of environment parameters on indoor pollutants' emission is of great significance for effective source control given the fact that people spend about 90% time indoor (Andrade et al. 2018; Xu et al. 2017).

The emission characteristics of air pollutants from building material is closely related to the indoor environment, and several studies have attempted to identify the correlations between environment parameters and emission rate (González-Martín et al. 2021; Ma et al. 2021). Given the emission parameters, the emission rate and diffusion effect of VOCs and formaldehyde under various working conditions can be accurately calculated using diffusion mass transfer models (Bai et al. 2020). Existing literature investigating the emission characters of VOCs or formaldehyde fall into two categories: experimental investigation and numerical simulation. Experimental method has been regarded as the most effective way to provide realistic results. And predictions made by numerical model normally need to be validated with experimental data to ensure the model accuracy (Liang et al. 2015; Yang et al. 2001). Hence, detailed experimental data can help researchers improve their simulation methods and better predict the release of VOCs or formaldehyde.

The emission of VOCs and formaldehyde can be influenced by various factors, such as temperature (Huang et al. 2020), relative humidity (Frihart et al. 2012), air exchange rate (Clausen et al. 2010; Liang et al. 2015), and even seasonality0 (Caron et al. 2020). Traditional emission determination methods typically analyze the effect of an individual parameter using experimental, or numerical and theoretical approach. Temperature and humidity are the most well-known environmental parameters that influence VOC emissions and many studies have been carried out in this field (Zhou et al. 2021; Liu et al. 2014). Zhang et al. (Zhang et al. 2007) investigated the influence of temperature on the diffusion coefficient (D) and the partition coefficient (K) of dry building materials through C-history analysis. Wang et al. (Wang et al. 2021) studied the impact of temperature on VOC emissions from wooden furniture, and pointed out that higher temperature can enhance molecular motions of pollutants inside the furniture, thus accelerating the emission rate of VOCs. It can be found that for dry building materials, the emission rate of major VOC types increases with increased temperature, and the influence of temperature is greater with higher temperature (Wal et al. 1997). For wet building materials, Zhou et al. (Zhou et al. 2020) proposed a mathematical model to depict the emission characteristic of VOCs during different drying stages. They found that increasing temperature could increase the growth rate of VOC concentration in the air. Higher temperature can significantly reduce the wet stage duration of wet building materials. With regard to the humidity, studies in this field can be classified to relative humidity (RH) and absolute humidity (AH). Traditionally, studies regarding the effect of humidity mainly focused on analyzing emission rates with variable RH. Frihart et al. (Frihart et al. 2010) studied the emission rate of formaldehyde from a UF-bonded particleboard and found that increasing RH have a significant effect on accelerating formaldehyde emissions. Parthasarathy (Parthasarathy et al. 2011) measured the formaldehyde emission of four composite wood surface materials and found that a 35% increase in RH can increase the emissions by 1.8 –2.6 times. Unlike RH analysis, very limited studies have focused on AH effect. However, as mentioned by Huang et al. (Huang et al. 2016), AH is directly related to moisture content of building materials and was demonstrated to be more appropriate for parametric analysis. And field test results conducted by Liang et al. (Liang et al. 2015) have proved the accuracy of this comment. Huang et al. (Huang et al. 2016) found that the formaldehyde and hexaldehyde emissions increased by 10 and 2 times when AH ranges from 4.6 g/m^3 to 19.6 g/m^3. The change of seasons will lead to the simultaneous change of both temperature and humidity. Many studies have verified the significant positive combined effects of temperature and humidity on VOCs emission. Xiong et al. (Xiong et al. 2016) analyzed the combined effect of temperature and RH on the emission rate of formaldehyde and VOCs, and the correlation between the emission rate and environmental parameters was also derived. Liang et al. (Liang et al. 2016) measured the combined effect of temperature and RH on the initial formaldehyde concentration (C_0) of a medium-density fiberboard, and results showed that the emission performance of the selected pollutants is much obvious in summer than that in winter for Beijing.

Based on the above reviews, it can be seen that in existing literatures, the emission analysis mainly focused on single factor while multiple factors have been less considered. This study carries out experimental research from temperature, humidity, and air exchange rate to find the effect of the three factors on the pollutant emission of dry and wet building materials. The pollutant emission capacity under different seasons has also been explored to provide experience for the health regulation of indoor environment. Hence, this paper aims at: (1) study the influence of temperature, relative humidity, air exchange rate (AER), and typical seasons on the emission of formaldehyde and total Volatile Organic Compounds (TVOC); and (2) compare the extent of the environmental parameters' influence on the pollution emission of dry building material and wet building material.

2. Experiment

2.1 Environmental chamber

Experiment of this work was performed in an environmental chamber, where the emissions characteristics of formaldehyde and TVOC from the building materials were measured. The size of the chamber is 1.65m×0.92m×2.04m with an effective volume of 2 m^3. The temperature in the chamber can be controlled in the range from 10 °C to 40 °C, and the relative humidity can be set between 30 and 85%, and the air exchange rate can be kept within 0-2.5 m^3/h.

The environment chamber mainly consists of nine parts: the test chamber, the temperature control system, the refrigeration humidity control system, the air cleaning system, the ventilation system, the air circulation system, the control system, and the gas sample system. The passive stainless-steel chamber and pipework ensure there was no absorption of formaldehyde and TVOC during the test. A refrigeration humidity control system was utilized for the air cooling and relative humidity control. A temperature control system equipped with heating and cooling sources was used for temperature control in the chamber. Purified air was supplied to the chamber after active carbon adsorption and purification in the air cleaning system.

Fig.1 Photo of the environmental chamber

2.2 Measuring devices

In this study, the portable detection instrument PMG-7240 was selected to detect the concentration of TVOC. The instrument has many obvious advantages such as short response time and wide detecting range. The sample flow rate of the detection instrument is 400 mL/min. Results given by the instrument is shown in volume percent, so a transform formula is needed to switch that to standard concentration, described as equations (1).

$$C(\mathrm{mg/m^3})=C_0(\mathrm{ppb})\times 10^{-3}\times\frac{M}{22.4}\times\frac{P}{101.3}\times\frac{273}{273+T} \qquad (1)$$

Where C is the mass concentration; C_0 is the volume concentration; M is molar mass of TVOC and in this paper the value is 56g/mol; P and T are the atmospheric pressure and temperature of the measuring point.

Formaldehyde was detected by fast-testing instrument PPM htv-M. The result of the instrument is shown in ppm and the transform formula is:

$$C(\mathrm{mg/m^3})=C_0(\mathrm{ppm})\times\frac{M}{22.4}\times\frac{P}{101325}\times\frac{273}{273+T} \qquad (2)$$

Where M is the molecular weight of formaldehyde and the value is set as 30.03g/mol.

Other measuring devices used in this experiment are shown in Table1.

Table1. Specifications of the measuring devices

Measured parameter	Device	model	Measuring range and accuracy
TVOC	Portable TVOC detector	PMG-7240	Measuring range: 0-100ppm； Resolution: 1ppm； Accuracy: ±3%
Formaldehyde	Fast-testing formaldehyde detector	PPM htv-M	Measuring range: 0~10pp； Resolution: 0.01ppm； Accuracy: ±2%
Pressure	Empty-box air-pressure instrument	DYM^3	Measuring range：800~1064hpa； Accuracy: Error ≤ 2.0hpa； Resolution: 1.0hpa
Temperature and humidity	Intelligent environment detector	KANOMAX-6531	Measuring range：0.0~60.0°C； Resolution: 0.1°C, Accuracy: ±0.5℃； Measuring range：0~100%； Resolution: 0.1%， Accuracy: 1.0%
Airflow rate	Precision anemometer	Testo-416	Measuring range：0~10m/s； Resolution: 0.01m/s， Accuracy: ±0.1m/s

2.3 Experimental materials

The dry building material used in the experiment is blockboard. The wet building materials are solvent based wood paint and water-based interior wall paint. The ordinary flat glass was selected as the carrier, as shown in Fig.2.

(a) blockboard, solvent based wood paint and aluminum foil tape

(b) Wood primers (the three from right) and finishes (the three from left) (c) Interior wall latex paint

Fig.2 Experimental materials

3. Experimental design

3.1 Experimental conditions

This paper aims to investigate the influence of temperature, humidity, air change rate (ARE), and seasonality on VOC emissions of building materials. Different temperature and humidity conditions were studied based on measurement data of nine different public buildings in Chongqing between 2012 - 2014.

Table 2. Experimental design for dry building material

a) the effect of temperature

Case	Temperature (°C)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Note
1	18±1	60±5	1.00±0.05	0.5	Four edges sealed
2	23±1	60±5	1.00±0.05	0.5	Four edges sealed
3	28±1	60±5	1.00±0.05	0.5	Four edges sealed

b) the effect of relative humidity

Case	Temperature (°C)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Note
1	23±1	45±5	1.00±0.05	0.5	Four edges sealed
2	23±1	60±5	1.00±0.05	0.5	Four edges

					sealed
3	23±1	75±5	1.00±0.05	0.5	Four edges sealed

c) the effect of air exchange rate

Case	Temperature (°C)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Note
1	23±1	45±5	1.00±0.05	0.5	Four edges sealed
2	23±1	45±5	0.50±0.05	0.5	Four edges sealed

c) the effect of seasonal conditions

Case	Temperature (°C)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Note
1	28±1	45±5	1.00±0.05	0.5	Four edges sealed
2	23±1	75±5	1.00±0.05	0.5	Four edges sealed
3	18±1	45±5	1.00±0.05	0.5	Four edges sealed

Table 4. Experimental design for wet building material

a) the effect of temperature

Case	Material	Temperature (℃)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Base
1	Wood Paint	18±1	45±5	0.5	0.5	Blockboard
2	Wood Paint	23±1	45±5	0.5	0.5	Blockboard
3	Wood Paint	28±1	45±5	0.5	0.5	Blockboard

b) the effect of relative humidity

Case	Material	Temperature (℃)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy (m^2·m^{-3})	Base

1	Wood Paint	23±1	45±5	0.5	0.5	Blockboard
2	Wood Paint	23±1	60±5	0.5	0.5	Blockboard
3	Wood Paint	23±1	75±5	0.5	0.5	Blockboard

c) the effect of seasonal conditions

Case	Material	Temperature (℃)	RH (%)	Air exchange rate (time·h^{-1})	Occupancy ($m^2 \cdot m^{-3}$)	Base
1	Wood Paint	18±1	45±5	0.5	0.5	Blockboard
2	Wood Paint	28±1	45±5	0.5	0.5	Blockboard
3	Wood Paint	23±1	75±5	0.5	0.5	Blockboard

3.2 Preparation of experimental materials

Two kinds of building materials were used in the experiment, including the blockboard (dry building material) and the paint (wet building material). The paint contained solvent-borne wood paint and interior wall latex paint. The size of blockboard used in the experiment is 500×1000mm and the edges are sealed with aluminum foil tape. The blockboards were stored at room temperature and protected from light. The solvent-borne wood paint used in this experiment was brushed on a 1m× 0.5m flat glasses on both sides. After 10 minutes when the painted surface was basically dry, it was put into the environmental chamber for testing. Due to the same quality of wood paint applied each time, it can be assumed that the film thickness in each experiment was the same. The interior wall latex paint was brushed to plasterboards with a size of 1m×0.5m. Similarly, the painted plasterboards were put into the environmental chamber for test after 10 minutes.

3.3 Experimental steps

Before the formal experiment, the performance tests of the environmental chamber were carried out, including the temperature and humidity accuracy test, air leakage rate test, etc. The performance tests were to ensure the experimental conditions satisfy the requirement of study.

Before the experiment was carried out, first, the environmental chamber was cleaned with deionized water (ASTMD5116-06, 2006). After the environmental chamber naturally dried, the chamber door was then closed. Furthermore, the experimental environment conditions were set. Moreover, when the setpoint of parameters inside the chamber reached stable state, the background concentration of the chamber was determined. Finally, the prepared experimental materials were placed in the slot of the environmental test chamber, as shown in Fig.3.

Fig.3 Experimental material in test chamber

The concentration of TVOC and formaldehyde was tested with the portable detection instruments at the sampling ports. The sampling time interval during the first three hours was 10 min, and then gradually increased to 20 min, 30min, 1h and 4h due to low gas-phase VOC concentrations. The experimental duration of each group was 72 hours. At this point, if the difference of two measured TVOC concentration in one time interval was within 5%, it is considered to be in equilibrium.

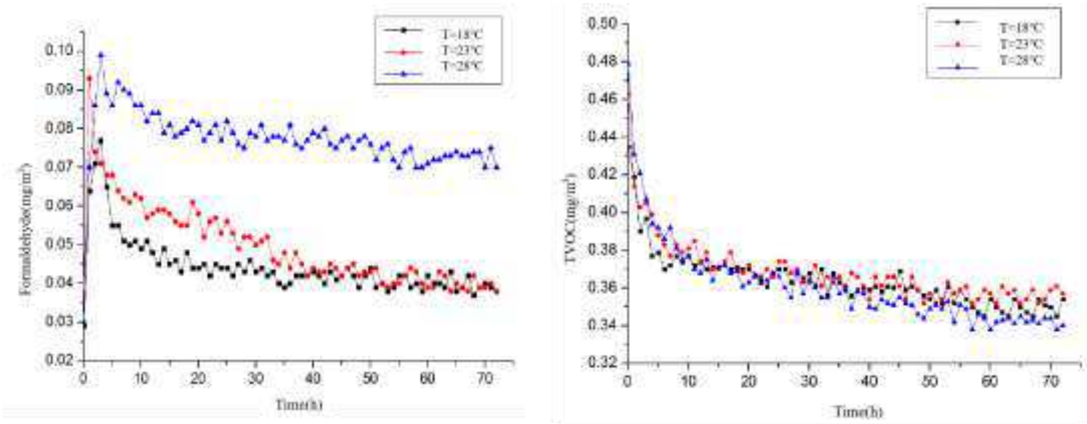
4 Results and discussion

4.1 The influence of environmental parameters on VOC emission

4.1.1 The influence of temperature on VOC emission

Fig.4 shows the influence of temperature on the concentration of formaldehyde and TVOC. It can be seen that the formaldehyde concentration descends to the lowest value at 18°C. Then concentration of formaldehyde increases significantly when the temperature reaches 28°C. The emission of formaldehyde changes significantly at the early 30 hours under the effect of the various temperature. This period is also called as active period. But after 30 hours, when the emission enters the stable period, the concentration curves tend towards stability and the concentration fluctuates within a certain range. For the max concentration of formaldehyde , the proportional relationship of that at 18 °C, 23 °C and 28 °C is $\mathrm{Max}_{18^{\circ}\mathrm{C}}$：$\mathrm{Max}_{23^{\circ}\mathrm{C}}$：$\mathrm{Max}_{28^{\circ}\mathrm{C}}$=1：1.2：1.29, and for the stable value, $\mathrm{Min}_{18^{\circ}\mathrm{C}}$：$\mathrm{Min}_{23^{\circ}\mathrm{C}}$：$\mathrm{Min}_{28^{\circ}\mathrm{C}}$=1：1.04：1.79. ($\mathrm{Min}_{18^{\circ}\mathrm{C}}$ means the stable concentration of formaldehyde at 18°C)

According to Fig.4(b), the TVOC emission of wood-based panel at different temperature are grossly similar. With time increases, the concentration of TVOC decreases clearly and finally achieves equilibrium. These results clearly show that changing temperature don't have significant difference on the trendline of emission, but will change the emission rate. Within the selected temperature range, increasing temperature will enhance the molecules emitting of formaldehyde but have negligible effect on TVOC emission.



(a) (b)

Fig. 4 The change trend of formaldehyde and TVOC concentration at different temperature

The stable concentration value of formaldehyde and temperature are correlated by non-linear method, as shown in Fig.5. The correlations can be described as equation (3). In this equation, the coefficients R^2 is 0.888, and the adjusted R^2 is 0.73605.

$$C = 0.01012e^{0.06879T} \tag{3}$$

Where C is the stable value of concentration and T is the temperature. It can also be seen from the equation that formaldehyde emission increase with temperature.

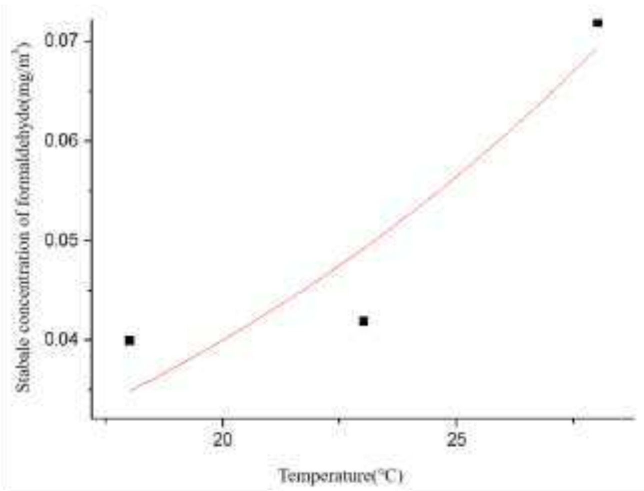


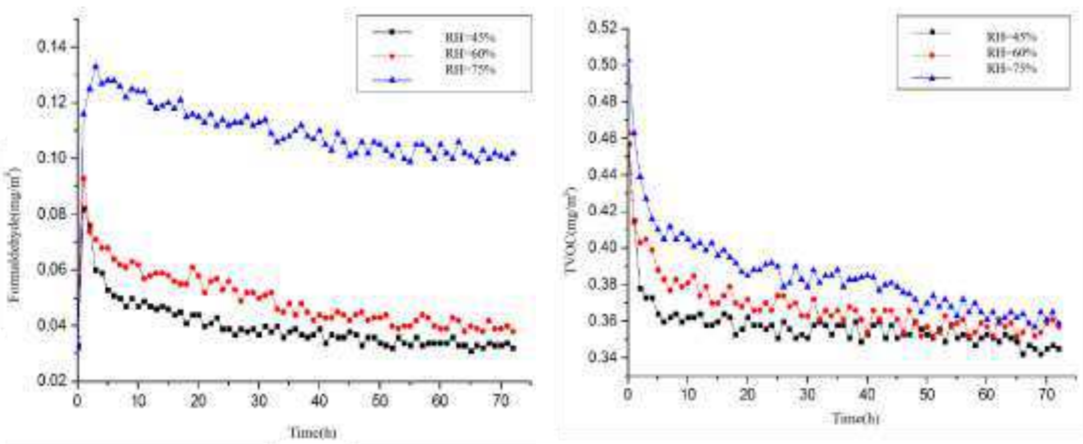
Fig. 5 Fitting curve of the formaldehyde concentration from blockboard at different temperature

4.1.2 The influence of relative humidity on VOC emission

The influence of relative humidity on formaldehyde and VOC emissions versus time is shown in Fig. 6. Fig.6(a) indicates that the variation trend of the formaldehyde concentration emitted from blockboard are essentially similar at different relative humidity (45%, 60% and 70%, respectively), first increasing rapidly and then beginning to decline. And then after the first 30 hours, the emission tends to be stable and this period is called to be steady stage. It can be clearly seen that the relative humidity has much effect on the emission flux. With increasing relative humidity, formaldehyde emitted from blockboard increases significantly. For the max concentration of formaldehyde, the proportional relationship of that at 45%, 60% and 75% is 1：1.13：1.63, and for the stable value, $Min_{45\%}$：$Min_{60\%}$：$Min_{75\%}$=1：1.2：3.02.

While from Fig.6(b), it can be observed that the variation trend of TVOC at different RH. The TVOC emission reaches the maximum at the very beginning and then gradually decline until stable after 30 hours, which is slightly different from the formaldehyde. The proportional relationship of the max concentration of TVOC is $Max_{45\%}$：$Max_{60\%}$：$Max_{75\%}$=1：1.01：1.1, and for the stable value, $Min_{45\%}$：$Min_{60\%}$：$Min_{75\%}$=1：1.02：1.04.

These results show that the increasing RH enhanced the emission of formaldehyde, and the promoting effect is more obvious for formaldehyde than for TVOC. The different degree of concentration change is maybe due to the different environment atmospheric pressure. From the viewpoint of physics, the change in ambient humidity will alter the environment atmospheric pressure, thus affecting the emission of pollutions. The solubility of formaldehyde in water makes the effect of relative humidity on formaldehyde emission more significant.



(a) (b)

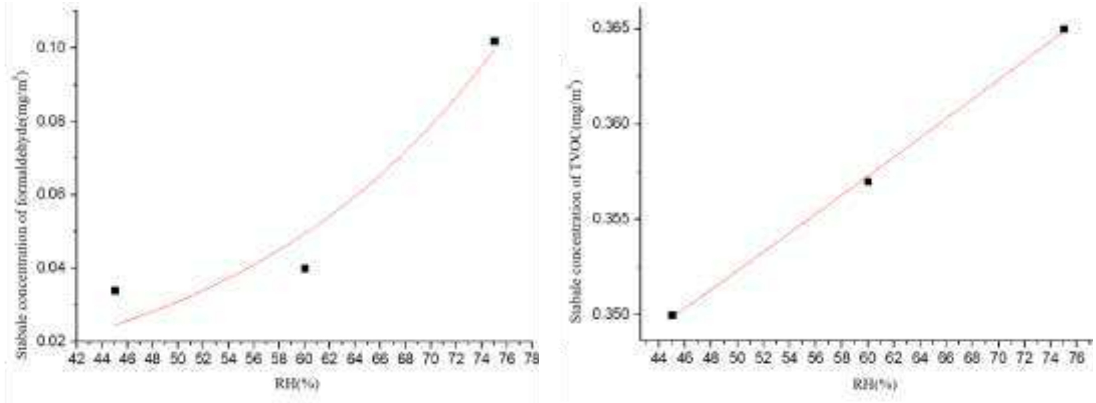
Fig. 6 The change trend of formaldehyde and TVOC concentration at different relative humidity

The stable concentrations of formaldehyde and TVOC in different humidity are fitted by nonlinear method, as shown in Fig. 7. The correlations can be described as equation (4). In equation (4a), the coefficients R^2 is 0.935, and the adjusted R^2 is 0. 86994. For equation (4b), the coefficients R^2 is 0.9979, and the adjusted R^2 is 0. 9989.

$$C = 0.00299 e^{0.04677\phi} \quad (4a)$$

$$C = 0.3285 e^{0.0014\phi} \quad (4b)$$

Where C is the stable value of concentration and ϕ is the relative humidity. It can also be seen from the equation that increasing humidity will increase the emission rate of formaldehyde and TVOC, and the growth trend is more obvious for formaldehyde than for TVOC (0.04677>0.0014).



(a) (b)

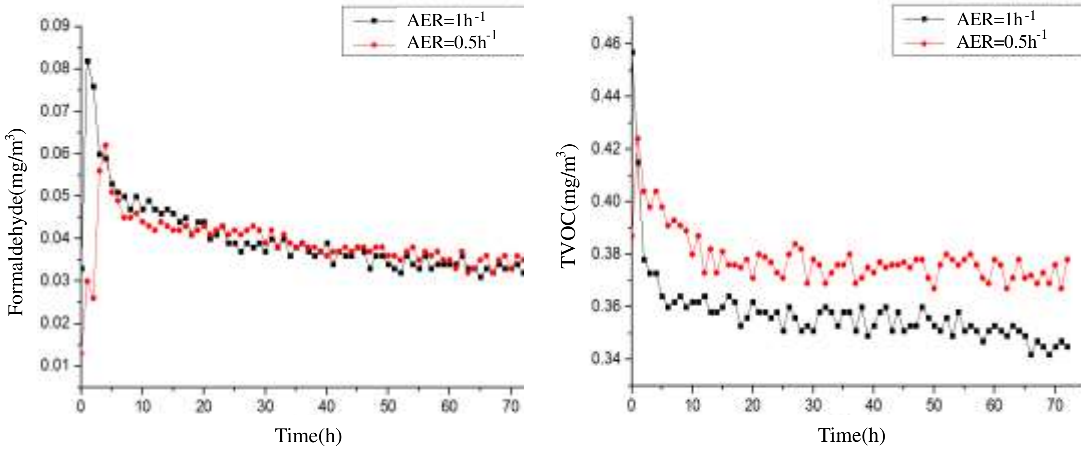
Fig. 7 The fitting curves of (a) formaldehyde and (b) TVOC concentration at different relative humidity

4.1.3 The influence of air exchange rate on VOC emission

Fig.8(a) illustrates the influence of air exchange rate (AER) on formaldehyde emission. When AER is 1 time·h^{-1} and 0.5 time·h^{-1}, the variation trend of formaldehyde against time is basically same, namely first increasing rapidly and then beginning to decline. The emission will become stable after 50 hours. Increasing ventilation times can quickly promote the formaldehyde emission rate. The maximum formaldehyde concentration at 1 time·h^{-1} is about 0.76 times than that at 1 time·h^{-1}. It is worth noting that there is no significant difference in stable formaldehyde concentration between different AER conditions. That is because with the increase of AER, the mass transfer coefficient will be increased and then promote the formaldehyde emission. But at the same time, the increasing AER promotes the exchange rate between indoor and outdoor air, thus diluting the indoor formaldehyde concentration. So, this opposite and combined effect leads to the negligible difference in formaldehyde concentration.

Fig.8(b) illustrates the influence of AER on TVOC emission. It can be seen that emission trend of TVOC under different AER value is basically the same. Unlike formaldehyde, the TVOC concentration is essentially stable after 30 hours. The maximum TVOC concentration at 1 time·h^{-1} is about 0.93 times than that at 1 time·h^{-1}, and 1.08 times for the stable TVOC concentration.

Therefore, increasing AER will cause some attenuation effects on formaldehyde and TVOC emission, and the effect is more obvious on TVOC than formaldehyde.

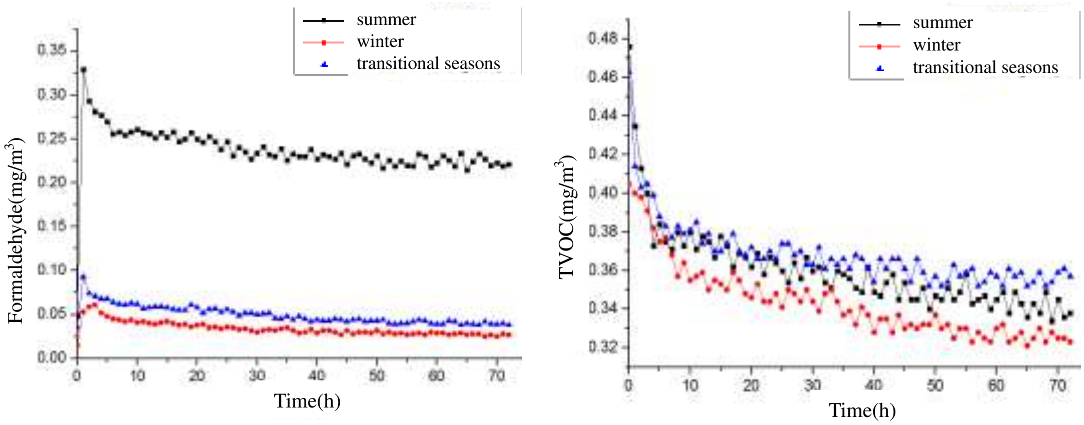


(a) (b)

Fig. 8 The change trend of formaldehyde and TVOC concentration with different air exchange rate

4.1.4 The influence of typical seasons on VOC emission

Fig.9 shows the VOC emissions from blockboard in different typical seasons. According to Fig.9 (a), we can observe that the formaldehyde emission in summer is much greater than that in winter and transitional seasons. Previous studies have shown that increasing temperature and humidity will both enhance the formaldehyde emission. In this section, the proportion of the maximum formaldehyde concentration in different seasons is Max_{summer}：Max_{winter}：$Max_{transitional\ season}$=1：0.18：0.28, and for stable value the relationship is Min_{summer}：Min_{winter}：$Min_{transitional\ season}$=1：0.12：0.17. By the combined effect of temperature and humidity, the formaldehyde emission is more active in summer. From Fig.9 (b), it can be seen that trendline of TVOC emission is basically in agreement with that of formaldehyde emission. For maximum TVOC concentration, the relationship is Max_{summer}：Max_{winter}：$Max_{transitional\ season}$=1：0.85：0.97, and for stable value the relationship is Min_{summer}：Min_{winter}：$Min_{transitional\ season}$=1：0.96：1.05. The influence of temperature and humidity is not that obvious compared to formaldehyde.



(a) (b)

Fig. 9 The change trend of formaldehyde and TVOC concentration in different typical seasons

4.2 Effect of environmental conditions on VOC emission from paint

4.2.1 Effect of ambient temperature on VOC emission of paint

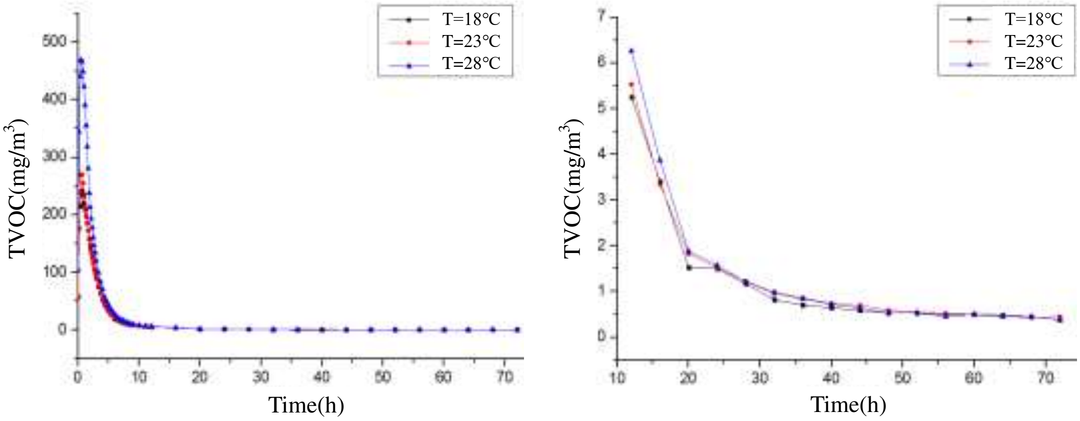
According to Fig.10, the concentrations of formaldehyde and TVOC both increased rapidly in an hour and then decreased sharply after reaching the peak. After 8 hours, the decrease rate slows down and finally stabilized. According to the attenuation rate of TVOC, the emission process can be divided into three stages:

The first stage is the initial emission stage (0-2h), where the concentration of TVOC would increase rapidly and evidently during this period. The phenomenon can be explained by the principle of concentration gradient. At the initial stage, the TVOC concentration is nearly zero in environmental chamber because the wet material has just been painted. The high concentration of free TVOC around the wet material leads to the rapid change of gas-phase VOC concentrations in the initial emission process. It is worth noting that the period is less than 2 hours for both experiments.

The second stage is the transition stage, TVOC concentration decreases rapidly from the max value and becomes stable during this period. The concentration difference of TVOC between the wet material and environmental chamber becomes slighter and then weakens the TVOC emission.

The final stage is the distribution stage. During this period, the TVOC emission becomes steady and the paint is completely dry. Remaining VOCs continuously spread to indoor air in a constant rate after inner diffusion. This stage is the main origin of indoor pollution.

Generally, temperature plays an important role on paint's TVOC emission. When the temperature raises from 18℃ to 23℃, the maximum TVOC concentration emitted from paint increased 12% and the stable TVOC concentration increased 2%. When the temperature raises from 18℃ to 28℃, the maximum TVOC concentration increased 94% and the stable TVOC concentration increased 6%.



(a)0-72h (b)12-72h

Fig. 10 The change trend of formaldehyde and TVOC concentration of paint at different temperatures

The stable concentrations of TVOC emitted from paint at different temperatures are fitted by nonlinear method, as shown in Fig. 11. The correlations can be described as equation 4. In equation (4c), the coefficients R^2 is 0.92172 and the adjusted R^2 is 0. 39303.

$$C = 0.39303e^{0.00562T} \qquad (4c)$$

It can be seen that increasing humidity will increase the emission rate of TVOC from paint.

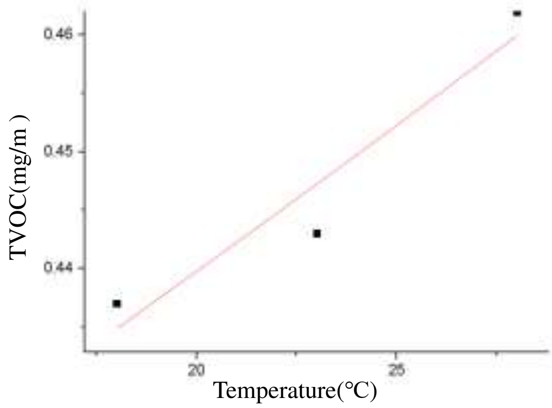


Fig. 11 Fitting curve of the TVOC concentration from paint at different temperature

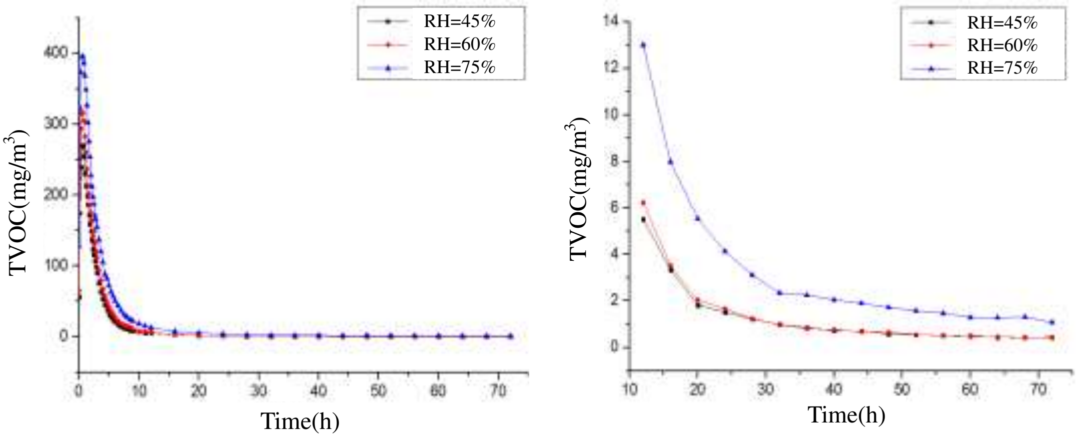
In a certain range, the temperature and TVOC emission are usually positively correlated. But with the increase of temperature, the paint is completely dry and thus restricts the diffusion of TVOC. Anyway, increasing temperature does not have much influence on TVOC emission during the final stage.

4.2.2 Effect of relative humidity on VOC emission of paint

Fig.12 shows the VOC emission of paint at different humidity. It can be seen that the concentration of TVOC increased rapidly in an hour and then fall sharply before eight hours. The relative humidity and TVOC concentration are positively correlated, and increased humidity will promote the emission rate of TVOC. When the relative humidity increased from 45% to 60%, the max TVOC concentration increased 17% and the stable concentration increased 4%. When the relative humidity increased from 60% to 75%, the max TVOC concentration increased 47% and the stable concentration increased 176%.

The TVOC stable concentration of paint at different humidity was fitted using nonlinear method, as shown in Fig.12. The correlations can be described as equation (4d). In equation (4d), the coefficients R^2 is 0.8993 and the adjusted R^2 is 0.7987.

$$C = 0.0397e^{0.04531\varphi} \qquad (d)$$



(a)0-72h (b)12-72h

Fig. 12 The change trend of formaldehyde and TVOC concentration of paint at different relative humidity

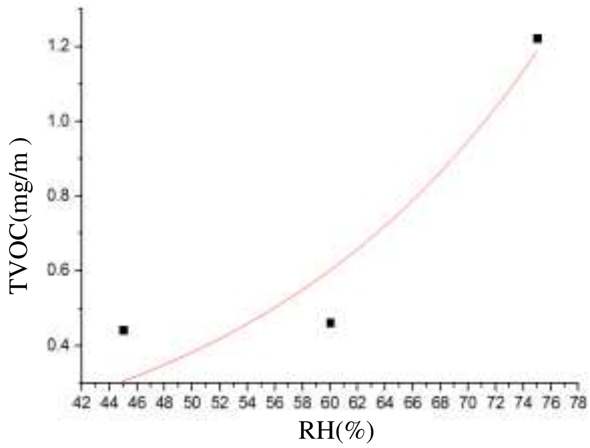
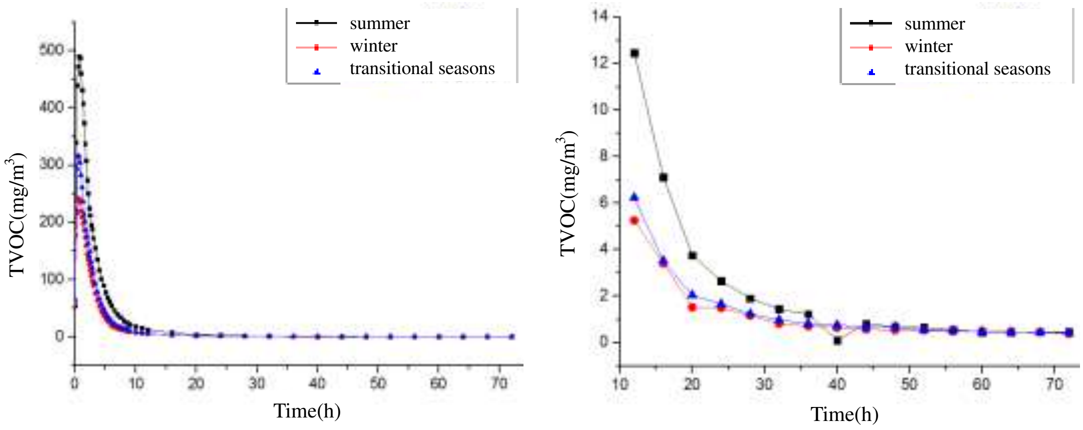


Fig. 13 Fitting curve of the TVOC concentration from paint at different relative humidity

During the initial and second stages, the increasing relative humidity accelerates the hydrolysis of various organic compounds in the wet paint, thus causing more organic molecules such as aliphatic hydrocarbon, aromatic, aldehydes, alcohols and ketones to leave the wet paint surface and enter the outside space, which promotes the emission of TVOC. In the final steady stage, the diffusion behavior of TVOC from paint is restricted by the dry layer. Hence, the influence of relative humidity on concentration curve is decided by the formation and structure of the dry layer.

4.2.3 Effect of typical seasons on VOC emission of paint

From Fig.14, it can be observed that the change of TVOC is basically the same in different seasons. There is no significant difference in stable concentration for different seasons, but the max concentration varies greatly. For maximum VOC concentration, the relationship is Max_{summer}：Max_{winter}：$Max_{transitional\ season}$=1：0.85：0.97. And for stable value, the relationship is Min_{summer}：Min_{winter}：$Min_{transitional\ season}$=1：0.96：1.05.



(a)0-72h (b)12-72h

Fig. 14 The change trend of formaldehyde and TVOC concentration of paint in different seasons

The above phenomenon is due to the combined effect of temperature and relative humidity. Higher temperature and humidity might play synergetic roles in increasing emission rate, which counteracts the resistance of dry layer.

5. Conclusion

(1) The VOC emission of dry materials and wet materials showed similar changing trends with different temperature, relative humidity, seasons and AER. The VOC concentration increased rapidly at the initial emission stage and then decreased sharply. The emission finally entered the steady stage where the concentration of VOC fluctuated within a certain range.

(2) For blockboards, increasing temperature and relative humidity has significant

influence on the emission rate, especially for formaldehyde. For paint, increasing temperature and relative humidity will enhance its TVOC emission. But changing temperature only has a small part to play in the emission of TVOC, while increasing humidity will promote both the max concentration and the stable concentration.

(3) Increasing AER has an opposite and combined effect on VOC emission of blockboards. For one hand, increasing AER will promote the emission rate of VOC and cause a higher peak value at the initial stage. For another, the concentration of VOC decreases under the dilution effect of ventilation. Generally, ventilation has a greater impact on TVOC emission.

(4) The TVOC stable concentration of blockboard and paint under different seasons is basically the same. But there is a significant difference in the max value with the highest values occurring in summer and the lowest emission occurring in winter. That is because the combined effect of high temperature and high humidity dramatically improve the emission rate of TVOC in summer, especially for formaldehyde.

Ethical Approval

Ethics approval is not required for this paper because this type of study is non-human.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

References

Amoatey, P., Omidvarborna, H., Baawain, M. S., Al-Mamun, A. (2018). Indoor air pollution and exposure assessment of the gulf cooperation council countries: A critical review. Environment international, 121, 491-506.

Andrade, A., Dominski, F. H. (2018). Indoor air quality of environments used for physical exercise and sports practice: Systematic review. Journal of environmental management, 206, 577-586.

ASTM Committee D-22 on Air Quality. (2010). Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products. ASTM International.

Bai, Y., Huo, L., Zhang, Y., Liu, J., Shao, H., Wu, C., Guo, Z. (2020). A spatial fractional diffusion model for predicting the characteristics of VOCs emission in porous dry building material. Science of The Total Environment, 704, 135342.

Billionnet, C., Gay, E., Kirchner, S., Leynaert, B., Annesi-Maesano, I. (2011). Quantitative assessments of indoor air pollution and respiratory health in a population-based sample of French dwellings. Environmental research, 111(3), 425-434.

Caron, F., Guichard, R., Robert, L., Verriele, M., Thevenet, F. (2020). Behaviour of individual VOCs in indoor environments: How ventilation affects emission from materials. Atmospheric Environment, 243, 117713.

Clausen, P. A., Liu, Z., Xu, Y., Kofoed-Sørensen, V., Little, J. C. (2010). Influence of air flow rate on emission of DEHP from vinyl flooring in the emission cell FLEC: Measurements and CFD simulation. Atmospheric Environment, 44(23), 2760-2766.

Frihart, C. R., Wescott, J. M., Birkeland, M. J.,Gonner, K. M. (2010). Formaldehyde emissions from ULEF-and NAF-bonded commercial hardwood plywood as influenced by temperature and relative humidity, Society of Wood Science and Technology Proceedings.

Frihart, C. R., Wescott, J. M., Chaffee, T. L., & Gonner, K. M. (2012). Formaldehyde emissions from urea-formaldehyde–and no-added-formaldehyde–bonded particleboard as influenced by temperature and relative humidity. Forest Products Journal, 62(7-8), 551-558.

Fu, N., Wei, P., Jia, Y., Zheng, X., Guan, J. (2021). Indoor volatile organic compounds in densely occupied education buildings of four universities: Target list, concentration levels and correlation analysis. Building and Environment, 191, 107599.

Gonzalez-Martin, J., Kraakman, N. J. R., Perez, C., Lebrero, R., Munoz, R. (2021). A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. Chemosphere, 262, 128376.

Huang, S., Xiong, J., Cai, C., Xu, W., Zhang, Y. (2016). Influence of humidity on the initial emittable concentration of formaldehyde and hexaldehyde in building materials:

experimental observation and correlation. Scientific reports, 6(1), 1-9.

Huang, S., Xiong, J., Zhang, Y. (2015). Impact of temperature on the ratio of initial emittable concentration to total concentration for formaldehyde in building materials: theoretical correlation and validation. Environmental science & technology, 49(3), 1537-1544.

Lang, I., Bruckner, T., Triebig, G. (2008). Formaldehyde and chemosensory irritation in humans: a controlled human exposure study. Regulatory Toxicology and Pharmacology, 50(1), 23-36.

Liang, Y., Caillot, O., Zhang, J., Zhu, J., Xu, Y. (2015). Large-scale chamber investigation and simulation of phthalate emissions from vinyl flooring. Building and Environment, 89, 141-149.

Liang, W., Lv, M., Yang, X. (2016). The combined effects of temperature and humidity on initial emittable formaldehyde concentration of a medium-density fiberboard. Building and Environment, 98, 80-88.

Liang, W., Yang, S., Yang, X. (2015). Long-term formaldehyde emissions from medium-density fiberboard in a full-scale experimental room: emission characteristics and the effects of temperature and humidity. Environmental science & technology, 49(17), 10349-10356.

Liang, Y., Xu, Y. (2015). The influence of surface sorption and air flow rate on phthalate emissions from vinyl flooring: measurement and modeling. Atmospheric Environment, 103, 147-155.

Liu, Z., Howard-Reed, C., Cox, S. S., Ye, W., Little, J. C. (2014). Diffusion-controlled reference material for VOC emissions testing: effect of temperature and humidity. Indoor Air, 24(3), 283-291.

Ma, N., Aviv, D., Guo, H., Braham, W. W. (2021). Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality. Renewable and Sustainable Energy Reviews, 135, 110436.

Main, D. M., Hogan, T. J. (1983). Health effects of low-level exposure to formaldehyde. Journal of occupational medicine, 896-900.

Pibiri, E., Omelan, A., Uhde, E., Salthammer, T. (2020). Effect of surface covering on the release of formaldehyde, acetaldehyde, formic acid and acetic acid from particleboard. Building and Environment, 178, 106947.

Salthammer, T., Mentese, S., Marutzky, R. (2010). Formaldehyde in the indoor environment. Chemical reviews, 110(4), 2536-2572.

Sparks, L. E., Tichenor, B. A., Chang, J., Guo, Z. (1996). Gas-phase mass transfer model for predicting volatile organic compound (voc) emission rates from indoor pollutant sources. Indoor Air, 6(1), 31-40.

Tichenor, B. A., Guo, Z., Sparks, L. E. (1993). Fundamental mass transfer model for indoor air emissions from surface coatings. Indoor Air, 3(4), 263-268.

Van der Wal, J. F., Hoogeveen, A. W., Wouda, P. (1997). The influence of temperature on the emission of volatile organic compounds from PVC flooring, carpet, and paint. Indoor air, 7(3), 215-221.

Wang, Yuanzheng, et al. (2021). Measurement of the key parameters of VOC emissions from wooden furniture, and the impact of temperature. Atmospheric Environment, 259, 118510.

Xiong, J., Zhang, P., Huang, S., Zhang, Y. (2016). Comprehensive influence of environmental factors on the emission rate of formaldehyde and VOCs in building materials: Correlation development and exposure assessment. Environmental research, 151, 734-741.

Xu, B., Chen, Z. (2017). The combined effects of temperature and electric fields on formaldehyde emission from building materials: Experiment and molecular dynamics simulation. International Communications in Heat and Mass Transfer, 87, 105-111.

Yang, X., Chen, Q., Zhang, J. S., Magee, R., Zeng, J., Shaw, C. Y. (2001). Numerical simulation of VOC emissions from dry materials. Building and Environment, 36(10), 1099-1107.

Zhou, X., Dong, X., Ma, R., Wang, X., Wang, F. (2021). Characterizing the partitioning behavior of formaldehyde, benzene and toluene on indoor fabrics: Effects of temperature and humidity. Journal of Hazardous Materials, 416, 125827.

Zhou, X., Gao, Z., Wang, X., Wang, F. (2020). Mathematical model for characterizing the full process of volatile organic compound emissions from paint film coating on porous substrates. Building and Environment, 182, 107062.

Zhang, Y., Luo, X., Wang, X., Qian, K., Zhao, R. (2007). Influence of temperature on formaldehyde emission parameters of dry building materials. Atmospheric Environment, 41(15), 3203-3216.

Statements and Declarations

Funding

The work described in this paper was fully supported by grants from Development Projects of Sichuan Province, China (Project No. 2021YFS0362)

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. The first draft and formal analysis of the manuscript was written by Zhu Cheng. The investigation and writing-review were performed by Moxin Wang, Nuoa Lei and Jie Xiong. The supervision and project administration were conducted by Ziyun Wang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.