The effects of temperature and humidity on the VOC emission rate from dry building materials

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Abstract. With the development of the economy and society, a wide variety of new building decoration and materials are widely used indoors. The concentration of pollutants such as formaldehyde, volatile organic compounds, benzene and ammonia in indoor air witnessed increase, causing increasingly serious indoor air pollution problems. Indoor building decoration materials are one of the main sources of indoor VOCs. In this paper, the emission law of VOCs in dry building materials with environmental conditions is studied. The environmental test cabin is used to test the formaldehyde and TVOC concentration released. The single factor variable method is used to study how different environmental conditions (temperature and relative humidity) affect the rate of formaldehyde and TVOC released from dry building materials. According to the results, increase of ambient temperature and relative humidity will promote the release of TVOC, which will affect its peak concentration and stable concentration, and the effect on formaldehyde release is more significant. This study clarified the release law of VOCs in artificial boards under different environmental conditions, which is of great significance for reducing indoor air pollutant levels and improving indoor air quality.

1. Introduction
Modern people spend 90% of their time indoors [1]. Indoor air quality is important to human health and has a greater impact on humans than outdoor air quality. In order to control the indoor air pollution, it is urgently needed to understand the emission law firstly. The experimental method is the most direct method to obtain the emission characteristics of building materials VOCs. At the same time, it can provide data support for theoretical models and verify the theoretical models. Renata et al. [2] studied the effect of room temperature on the amount of formaldehyde and VOCs released from the floor. The experimental results show that the concentrations of formaldehyde and VOCs are low at 23 °C and 29 °C. At 50 °C, the floor will release higher concentrations of formaldehyde and VOCs, and the concentration will gradually decrease as the test time increases. Shaodan Huang et al. [3] indicate that Cm,0 changes significantly with RH in the range of 20%~85. Furthermore, a novel correlation to describe the relationship between the emission rate and RH is derived theoretically. However, the effect of temperature and humidity on TVOC or formaldehyde emission is not very clear. This is partially due to a lack of understanding of the emission mechanism, and the experiment carried out in experimental test cabin to clarify the effect of temperature and humidity on formaldehyde and TVOC emission of wood-based panel is not very comprehensive.

2. Method or Experimental
2.1. Experimental room
This experiment was carried out with an environmental test cabin (HJC-1 type) produced by Shanghai Buqing Building Technology Development Co., Ltd. Outer cabin size is: length × width × height=1.65
m×0.92 m×2.04 m = 3.096m³. Effective capacity of the cabin is 2m³. Temperature adjustment range is 10 ~ 40℃. Relative humidity adjustment range is 30~85%. Inlet flow range is 0~2.5m³/h. Figure 1 shows the entity and system diagrams of the environmental test cabin.

2.2. Analytical instruments

Main instruments of the experiment are: HJC-1 type environmental test cabin (Shanghai Buqing Building Technology Development Co., Ltd.), PPMhtv-m type formaldehyde detector (Formaldemeter Company, UK), ppbRAE Plus PGM-7240 Portable TVOC Detector (RAE, USA), digital Thermometer 485-2 (Dwyer, USA), aneroid barometer (DYM3), intelligent Environment Detector (KANOMAX 6531). The instruments used in this experiment are calibrated to meet the test requirements.

Table 1. Parameters of test instruments.

| Measurement parameter | Instrument Type | Parameter |
|-----------------------|-----------------|-----------|
| Formaldehyde          | Formaldehyde detector | Range: 0~10ppm; accuracy: ±2%; resolution: 0.01ppm; warm-up time: 60s; response time: <60s |
| TVOC                  | TVOC Detector PPMhtv-m | Range: 0~10ppm; accuracy: ±2%; resolution: 0.01ppm; warm-up time: 60s; response time: <60s |
| TVOC                  | ppbRAE Plus PGM-7240 | Range: 1ppb-9999ppb; resolution: 1ppb; measurement accuracy: ±3% of the calibration point |
| Air pressure          | Aneroid barometer DYM3 | Range: 800~1064hpa; error is not more than 2.0hpa; minimum division value 1.0hpa |
| Temperature and humidity | Digital Thermometer 485-2 | Temperature range: -30.0 ~ 85.0 °C; resolution: 0.1 °C; Accuracy: ±0.5 °C; humidity range: 0 ~ 100%; resolution: 0.1%; accuracy: ±2.0% |
| Air velocity          | Intelligent Environment Detector KANOMAX 6531 | Range: 0~10 m/s; resolution 0.01 m/s, accuracy ±0.1 m/s |

2.3. Experimental materials

We purchased a brand of Chinese fir blockboard (1200mm×2400mm×15mm) from the building materials market, and cut into small pieces of 500mm×1000mm and stored it in the dark at room temperature. We used formaldehyde-free aluminum foil tape to seal the four end faces.

2.4. Experimental protocol

The purpose of this experiment was to study the release of volatile organic compounds from dry building materials under different temperatures and relative humidity. The choice of temperature and humidity is based on the analysis of the measured data of indoor air quality of nine public buildings in Chongqing from 2016 to 2018. The experimental temperature and humidity parameters are shown in Table 2.
Table 2. Experimental scheme for research on release law of dry building materials VOCs.

| Working condition | Temperature (℃) | Relative humidity (%) | Air exchange rate (times·h⁻¹) |
|-------------------|-----------------|-----------------------|-------------------------------|
| 1                 | 23±1            | 45±5                  | 1.00±0.05                     |
| 2                 | 23±1            | 60±5                  | 1.00±0.05                     |
| 3                 | 23±1            | 75±5                  | 1.00±0.05                     |
| 4                 | 18±1            | 60±5                  | 1.00±0.05                     |
| 5                 | 28±1            | 60±5                  | 1.00±0.05                     |
| 6                 | 18±1            | 45±5                  | 1.00±0.05                     |
| 7                 | 28±1            | 75±5                  | 1.00±0.05                     |

Before the experiment, the inner wall of the environmental cabin was cleaned with cotton gauze washed with distilled water until the inner wall was dry. Adjust the temperature and relative humidity required for the experiment. After the cabin has reached the required conditions and stabilized, place the tested panel into the environmental cabin. The duration of the experiment is 72 hours. We measured every 10 minutes for the first 3 hours, and measured every hour thereafter; the concentration of formaldehyde and TVOC are measured separately. In order to reduce the experimental error and improve the reliability of the data, the reading is taken three times and the average is recorded as the measured value of this time.

3. Results and discussion

3.1. Effect of temperature on the emission of VOCs from wood-based panels

The relative humidity is 60 ± 5%; the air exchange frequency is 1.00±0.05 times/h, and the four end faces of the artificial board are sealed with aluminum foil tape. The temperature is set to 18±1°C, 23±1°C, 28±1°C respectively. The results are shown in Figures 2 and 3.

It can be seen from Figure 2 that the release tendency of formaldehyde on wood-based panels is similar at different temperatures, and it is released violently in a short time. After reaching the maximum concentration, it gradually decreases with time. Finally, the formaldehyde concentration tends to be stable and reaches equilibrium. Note that the higher the temperature, the greater the effect on the formaldehyde release concentration over the selected temperature range. When the temperature is 18°C, the maximum concentration of formaldehyde released from the artificial board appears around 3h, and is 0.077mg/m³. When the temperature is 23°C, the maximum concentration appears at about 1h, and is 0.093mg/m³. When the temperature is 28°C, the maximum concentration appears at around 6h, and is 0.099 mg/m³. In the first 30 hours, the amount of formaldehyde released changed significantly with time. At 18°C, 23°C and 28°C, the equilibrium concentrations are 0.038mg/m³, 0.039mg/m³ and 0.073mg/m³, respectively. Experiments show that changing the temperature does not change the release tendency of formaldehyde in the artificial board, and only changes the release rate of formaldehyde. The higher the temperature, the greater the effect of formaldehyde release concentration on the wood based panels over the selected temperature range, and the longer the time required for the release of formaldehyde from the artificial board to reach the maximum concentration.

The main reasons for the influence of temperature change on the formaldehyde emission of artificial board are: the temperature rise in the environmental cabin accelerates the thermal movement of formaldehyde molecules and promotes the release of free formaldehyde left in the board during the production process. The increase in temperature also changes the pore structure characteristics of the artificial board, resulting in a decrease in the adsorption capacity to formaldehyde, which is favorable for the release of internal formaldehyde. In addition, the hemicellulose in the wood undergoes decomposition under high temperature conditions, and the methoxy bond cleavage releases a small amount of formaldehyde. Under the combined effect of these factors, formaldehyde release in wood-based panels increases with increasing temperature.
Figure 2. Formaldehyde emission at different temperature

The release trend of TVOC on wood-based panels at different temperatures is roughly similar, as Figure 3 shows. At the beginning, the concentration is the maximum, which gradually decreases with time, until the TVOC concentration in the cabin reaches equilibrium, and the curve tends to be stable. When the relative humidity is 60% and the number of air changes is 1 time/h, the temperature change has little effect on the TVOC release concentration of the artificial board within the selected temperature range. When the temperature is 18 °C, 23 °C and 28 °C, the maximum TVOC release concentration is 0.435 mg/m³, 0.463 mg/m³ and 0.479 mg/m³ respectively. After reaching the maximum concentration, the TVOC concentration gradually decreased with time. During the first 12 hours, the TVOC release rate changed significantly with time, and then the TVOC release rate slowed down and gradually became stable. The equilibrium concentration is 0.350 mg/m³ at 18 °C, 0.359 mg/m³ at 23 °C, and 0.339 mg/m³ at 28 °C. Experiments show that changing the temperature does not change the release tendency of TVOC, and has little effect on the TVOC release rate. When the temperature rises, the maximum concentration of TVOC release from the wood-based panel increases, but the temperature increase has no significant effect on the equilibrium concentration of TVOC in the experimentally selected temperature.

From the perspective of mass transfer, as the temperature increases, the internal mass transfer resistance decreases, the diffusion coefficient D increases, and the VOCs concentration in the cabin increases. At the same time, the temperature change will also affect the separation coefficient K between the VOCs concentration of the building material surface and the VOCs concentration of the material phase. The temperature rises and the separation factor K decreases. In the early stage of release, the diffusion coefficient and the separation factor work together, so that the temperature change has a significant effect on the emission of VOCs on the artificial board. At the late stage of release, the diffusion coefficient mainly acts.

Figure 3. TVOC emission at different temperature
3.2. Effect of relative humidity on the emission of VOCs from wood-based panels  
At a temperature of 23 ± 1°C, the number of air changes is 1.00 ± 0.05 times/h, and the four end faces of the wood-based panel are sealed with aluminum foil tape. The relative humidity is set to 45 ± 5%, 60 ± 5% and 75 ± 5%. The results are shown in Figures 4 - 5.

It can be seen from Figure 4 that different relative humidity has no significant effect on the release tendency of formaldehyde in artificial board. Formaldehyde is released violently in a short time. After reaching the maximum concentration, it gradually decreases with time and finally stabilizes. The higher the relative humidity in the selected relative humidity range, the greater the effect on the formaldehyde release concentration of the wood-based panel. Changing the relative humidity also has an effect on the time at which the formaldehyde release concentration reaches a maximum. When the relative humidity is 45%, 60% and 75%, the maximum concentration of formaldehyde emission appears at about 1h, 2h and 3h, the maximum concentration is 0.082 mg/m³, 0.093 mg/m³ and 0.133 mg/m³ respectively. At about 50 h, the concentration of formaldehyde released gradually decreased with time and became stable. At conditions of 45%, 60%, and 75%, the equilibrium concentrations are 0.033 mg/m³, 0.039 mg/m³ and 0.101 mg/m³ respectively.

The main reason is that the adhesive urea-formaldehyde resin used in the artificial board has poor water resistance, and the relative humidity in the environment accelerates the breakage of hydrophilic groups. Formaldehyde is released even if it does not evaporate in a short time; free formaldehyde will remain in the board and gradually release, causing long-term indoor formaldehyde pollution. Moreover, the relative humidity increases, the pore structure in the wood board will swell, resulting in a change in the pore structure, which is beneficial to the release of formaldehyde. Because formaldehyde is easily soluble in water, water vapour has a certain absorption effect on formaldehyde. The humidity increases, so that the water vapour content in the air rises. Under the combined effect of the above factors, the amount of formaldehyde released from the artificial board eventually increases with the increase of relative humidity.

![Formaldehyde emission at different relative humidity.](image)

It can be seen from Figure 5 that the release tendency of TVOC in wood-based panels is similar under different relative humidity, and gradually decreases with time from the maximum concentration until the TVOC concentration in the cabin tends to be stable.

The effect on the release of TVOC concentration on wood-based panels is slight. The amount of formaldehyde released in the first 12h changed significantly with time. When the relative humidity is 45%, 60% and 75%, the maximum concentration of TVOC release is 0.475 mg/m³, 0.463 mg/m³ and 0.503 mg/m³ respectively, and the equilibrium concentrations are 0.346 mg/m³, 0.359 mg/m³ and 0.362 mg/m³. Experiments show that changing the relative humidity does not change the release tendency of wood-based panel TVOC, but change the TVOC release rate; the relative humidity rise will promote the release of TVOC, but the effect is small. The time required for the TVOC concentration to reach...
equilibrium in high humidity is longer, and the time required to reach equilibrium at 75% is about 4 times that of 45%. Moreover, the equilibrium concentration reached is relatively close.

The effect of relative humidity changes on formaldehyde and TVOC release rates is because the wood-based panels are porous materials, and the water molecules and VOCs in the material each occupy the pore space. When the relative humidity in the environment increases, the water vapour pressure in the air increases, thereby reducing the water vapour pressure in the environment and the gradient of the water vapour pressure inside the sheet, so that the rate of evaporation of water molecules inside the wood panel to the outside is reduced. The pore space occupied by water molecules is relatively large, and the pore space occupied by VOCs molecules becomes smaller, which promotes the release of VOCs from the inside of the artificial board.

The most suitable relative humidity of the human body is 45% - 65%. The experimental results show that the release rate of formaldehyde and TVOC in the artificial board is relatively slow in this relative humidity range, and the indoor relative humidity can be adjusted within this range to slow the release rate of formaldehyde and TVOC. This method can only temporarily reduce the formaldehyde and TVOC concentrations released from indoor wood-based panels.

![Figure 5. TVOC emission at different relative humidity.](image)

4. Conclusions
1) The release trend of formaldehyde and TVOC in wood-based panels does not change with changes in temperature and relative humidity. The release process of formaldehyde from wood-based panels can be divided into three stages: initial rapid release phase, stable release phase, and long-term slow release phase. The release process of TVOC can be divided into an active period and a stable period in which the amount of release changes significantly with time.
2) Increasing the temperature or increasing the humidity, the release rate of formaldehyde and TVOC in the artificial board increased to different degrees. The change of temperature or humidity has a greater effect on the release of formaldehyde from the artificial board, and has less influence on the release of TVOC. Under the combined action of temperature and humidity, the effect of formaldehyde and TVOC release on wood-based panels is more intense.

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