

Effects of Environmental Conditions on the VOC Sorption by Building Materials - Part I: Experimental Results (RP-1097)

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ABSTRACT

Three typical kinds of building materials (painted drywall, ceiling tile, and carpet) have been tested to study the effects of environmental conditions (temperature, relative humidity, and air velocity) on the sorption of volatile organic compounds (VOCs) by building materials. It was found that the effects of environmental conditions on sorption were insignificant for the painted drywall due to its weak sink strength as compared to the experimental uncertainty. The effect of relative humidity was generally small on the sorption of most compounds on ceiling tiles and carpet. However, the increase of temperature and air velocity may affect the amount of VOCs adsorbed by the ceiling tiles and carpet.

KEYWORDS: VOC, Sorption, measurement, building material, indoor air quality

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ABSTRACT

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INTRODUCTION

Materials capable of depositing, adsorbing, and/or accumulating pollutants such as volatile organic compounds (VOCs) can influence the indoor air quality (IAQ) of a building during its entire service life (Nielsen 1987). Due to the potentially serious health effects from long-term exposure to low pollutant concentrations, an accurate

characterization of the VOC sorption by building materials and its impact on IAQ is important.

The VOC sorption by building materials is a complicated phenomenon. The sorption depends on numerous factors, including the material properties, the VOC type, and the environmental conditions, such as temperature (Tichenor et al. 1991; van der Wal 1994), relative humidity (Kirchner et al. 1996), air velocity (Kjaer and Tirkkonen 1996), and VOC concentration in the air (Kephelopoulos et al. 1996). At present, studies of the effects of sorption on VOCs are mainly conducted by experiments using environmental chamber testing or microbalance measurements. The experiments are usually conducted under a set of specific environmental conditions (e.g., at 23°C temperature, 50% relative humidity, and one time air exchange rate per hour). There is a lack of information concerning the effects of different environmental conditions on VOC sorption by building materials, while such information is essential for accurate and reliable assessment of the impact of building materials on indoor air quality. To fill this knowledge gap, ASHRAE has sponsored this research to determine how significantly the environmental conditions can affect the VOC sorption by building materials, and if existing models are adequate to account for the VOC sorption effects. This paper presents the experimental results of the impact of the environmental conditions on VOC sorption. A companion paper will evaluate various existing sorption models.

EXPERIMENTAL METHOD AND TEST FACILITY

Overview of the Experimental Method

Our previous paper (Zhang et al. 2002) has reviewed different experimental methods that study the sorption phenomenon. The review concluded that the small-scale chamber test method was most widely used in sorption study, and was also the most useful and affordable method. Therefore, the present investigation implemented the small-scale chamber test method, as shown in Figure 1a. Each test contained an adsorption and desorption period (Figure 1b). In the adsorption period, air with a constant concentration of the selected VOCs was supplied to a small test chamber, in which a test specimen was placed. During the desorption period, the VOC injection was stopped while the clean air supply to the chamber was maintained at the same flow rate. During the test, air samples were taken at the chamber exhaust using adsorbent tubes, and they were analyzed by a thermal desorption-GC/FID (Gas Chromatogram/Flame Ionization Detector) system to determine the VOC concentrations at the chamber exhaust. The VOC sorption by the test specimen was revealed by comparing the measured VOC concentrations with the theoretical values under the no-sink or no-sorption condition (Figure 1b). The tests were conducted under different environmental conditions to investigate the effects of relative humidity, temperature, and air velocity on the sink strength of different materials. The test facilities consisted of a small-scale chamber sorption test system, four small chambers, and an air sampling and chemical analysis system.

The Small-Scale Chamber Sorption Test System

The small-scale chamber sorption test system consists of a clean air supply system, a VOC injection unit, chamber assemblies, a humidity control system, a temperature control system, and a data acquisition system. Figure 2 is the schematic of the whole chamber system. The following discusses each component in detail.

- a) Clean air supply system: The clean air supply system consists of a compressed air source, particulate and oil filters, a dehumidifier, a mass flow meter, a catalytic oxidizer, a pressure regulator, and a toggle valve, as indicated in Figure 2. The air from the oil-free compressor (or the building-compressed air) first passes through the particulate filters and the oil filter to have its particulate and oil vapor removed. Then it goes through the desiccant dehumidifier to remove the moisture in the air. To ensure accurate reading from the mass flow meter, a pressure regulator was installed in front of the flow meter to maintain a constant inlet pressure to the flow meter. After the air has gone through the catalytic oxidizer for VOC removal, it becomes clean (TVOC <math><10\mu\text{g}/\text{m}^3</math> and individual VOC <math><2\mu\text{g}/\text{m}^3</math>). Then the air goes through another pressure regulator in order to maintain a constant inlet pressure to the chamber system. Finally, the air is split into four channels and supplied to each individual chamber system after humidification.
- b) Humidity control system for each chamber: For each chamber, the humidity control was accomplished by bubbling a portion of the air stream through the water impingers at a controlled temperature. The saturated air is then mixed with dry air to achieve the desired humidity. For the humidity conditions used in this study (25%, 50% and 80%), the system can control the humidity level to an accuracy of $\pm 3\%$.
- c) Temperature control system for all the chambers: Temperature control for the small chambers was achieved by placing the test chambers inside a large insulated enclosure, in which temperature can be accurately controlled. Since the small chambers are located inside the big enclosure, and the walls of the chambers are all made of stainless steel (a good conductor for heat), their temperature was equal to that of the big box after giving enough time. The test of the system showed that the temperature of the small chamber was controlled with an accuracy of $\pm 0.5^\circ\text{C}$.
- d) Chamber assemblies: This study used four electropolished 316 stainless steel chambers with a volume of 50 liters (0.5 x 0.4 x 0.25m, or 20 x 16 x 10 in.) as specified by ASTM D5116 (1997). Teflon gaskets were used to airtight-seal the edges of the chamber. The chamber itself has a negligible sorption effect. This investigation also used multi-port inlet and outlet manifolds, as recommended by ASTM D5116, to ensure adequate mixing of the air inside the chamber (Zhang et al. 1997).
- e) VOC injection unit: The VOC injection unit is to supply a constant stream of VOCs to the chamber system through a dynacalibrator. The dynacalibrator has an internal pump that takes in ambient lab air and then cleans it through a series of filters. Afterwards, the clean air runs through a temperature-controlled glass chamber

containing permeation tubes that carry in VOCs at the desired VOC concentration level. The operating temperature was maintained at 80°C for all the tests in this study.

- f) Data acquisition system: The data acquisition system consisted of a data logger and necessary software as well as ten sensors. The sensors include one mass flow meter for measuring the total airflow rate to the system, one temperature/humidity sensor for measuring temperature and relative humidity, and seven thermocouples for measuring the temperatures at different locations.

Velocity Control in a Test Chambers

The 50 L chambers were designed to allow the control of the air velocity over the specimen. This enabled the study of the velocity effect, as indicated in Figure 3. A small DC fan blew air through a narrow slot inside the chamber to create a semi-attached circulating air flow. The velocity could be varied by adjusting the voltage supplied to the DC fan and changing the fan speed. The velocity distribution over the specimen was sufficiently uniform (Zhang 2002).

Air Sampling and Chemical Analysis System

ASTM D6196 (1997) recommended measuring the VOC concentrations by drawing a certain amount of the air through an adsorbent tube, and then analyzing the sample by a thermal desorption-GC/FID (TD-GC/FID) system. A pocket digital sampling pump was used for sampling. The adsorbents used in this study were Carbopack C (60/80 mesh) and Carbopack B (60/80 mesh) at a 2:1 ratio (200mg vs 100mg). The thermal desorption-GC/FID system used can analyze 50 tubes automatically. The GC column used was a DB-5MS (0.32 mm inner diameter, 0.25 μ m film thickness, 60m long) capillary column. The GC oven program used was: initial temperature 60°C, ramp at 15°C/min to 200°C, then ramp at 30°C/min to 300°C and hold for 7 mins.

EXPERIMENTAL DESIGN

This section discusses the detailed experimental design to study the effects of the environmental conditions on the sorption process. It includes the discussion of test materials, test conditions, test period, air sampling intervals, test procedure and estimation of experimental uncertainties.

Test Materials

With the above-mentioned test facilities, this investigation tested three typical building materials bought from a retail store - painted gypsum wallboard (painted drywall), ceiling tiles, and carpeting. These three materials cover a large surface area in buildings and also represent three very different surface characteristics, as shown in Figure 4. The surface of the painted drywall is smooth. The surface of the ceiling tile is a little coarse, while the surface of the carpeting is of fiber structure, which is very coarse. Therefore, they can provide a broad range of sorption data for model evaluation and development.

Each material was cut into a 45.2 cm by 20.2 cm (17.8 in. by 8.0 in.) test specimen. In order to minimize the edge effect, the specimens were placed in a stainless steel specimen

holder (45.2 cm by 20.2 cm or 17.8 in. by 8.0 in.) and the edges of the specimen were sealed by parawax (0.10 cm in width or 0.04 in.). This gave an exposed surface of 45 cm by 20 cm (17.7 in. by 7.9 in.). Such preparation of the test specimen was needed to ensure that the sorption occurs only through the top surface of the material. This allows for exact boundary conditions to be known for model evaluation and development. After waxing the edges, the specimens in the holder were kept in a well-ventilated fume hood for over six months before the tests. Such a long time of preconditioning under a well-ventilated condition would minimize the amount of VOCs remaining in the material.

Test VOCs

The six test VOCs selected were ethylbenzene (EB), benzaldehyde (BZA), decane (DEC), 1,4-dichlorobenzene (DCB), undecane (UND) and dodecane (DOD). They represent different types of VOCs, including alkanes, aromatics, aldehydes, and chlorine-substituted compounds, and also cover a wide range of vapor pressures, as shown in Table 1. The concentrations of the VOCs in the chamber ranged from 0 to about 1.0 mg/m³ during the tests. These concentration levels are similar to those (from 0 to 0.5 mg/m³) typically found indoors (Brown et al. 1991).

Test Conditions

The test conditions included three temperature levels, 10.5°C, 23°C and 35°C, three humidity levels, 25%, 50% and 80%, and two velocity levels, 0.05m/s and 0.62m/s (Table 2). These levels cover a wide range of typical indoor conditions, even in building bake-outs or material storage rooms. A total of eighteen material tests were conducted for the three materials. In addition to the material tests, one empty chamber test was conducted to quantify the sink effect of the chamber walls.

Test Period and Air Sampling Intervals

The adsorption period for all the carpet tests was 168 hrs and the desorption period was 336 hrs. The exception was the reference carpet test, in which the adsorption period was 1056 hrs and the desorption period was 1056 hrs. The adsorption period for all the painted drywall and ceiling tile tests was 72 hrs and the desorption period was 120 hrs. The time for each test has been proved to be sufficient by theoretical modeling (Zhang 2001). Air samples were collected at the chamber exhaust and inlet. The sampling flow rate was set at 150ml/min to minimize the sampling effect on the flow field in the test chamber. The sampling volume ranged from 0.75l to 10.0l depending on the VOC concentration level in the chamber. The air from the inlet was sampled once per day to ensure that the small-scale chamber test system was working properly. Air samples were taken from the exhaust at 15 mins, 30 mins, 1 hr, 1.5 hrs, 2.0 hrs, 2.5 hrs, 3.0 hrs, 3.5 hrs, 4.0 hrs, 4.5 hrs, 5.0 hrs, 5.5 hrs, and 6.0 hrs after the system was started. The sample schedule above shows that it was especially intensive in the beginning. This sampling schedule was significantly more frequent than that of previous studies, because:

- (a) measurement errors are always present. More sampling can reduce random errors
- (b) more data points will make the model validation more accurate and reliable;
- (c) more data points in the late period of the adsorption or desorption process can reveal the slow diffusion process and are crucial to data regression and statistical analysis.

Test Procedure

Before each experiment, the test chamber was cleaned with an alkaline detergent and rinsed with de-ionized water. A test material specimen was then placed in the test chamber, supplied with clean humidified air at an air change rate of one air change per hour, for two days. This would ensure that the background VOC concentration with the test specimen would be negligible ($<2\mu\text{g}/\text{m}^3$). The adsorption phase started after the injection of VOCs to the chamber inlet. When the adsorption period was completed, the desorption phase was started immediately by stopping the VOC injection.

Analysis and Estimation of Experimental Uncertainties

No measurement, no matter how carefully designed, can be completely free of uncertainties. Therefore, estimating uncertainties and reducing them to an acceptable level is very important in any experiment. This section analyzes the uncertainties associated with the sorption tests. Since both systematic errors and random errors can cause uncertainties (Holman 1994), the following will discuss their sources. Hereafter, we use the following nomenclature:

- U = the overall uncertainty
- U_r = the overall relative uncertainty
- B = the systematic error (bias)
- B_r = the relative systematic error
- P = the random error (precision)
- P_r = the relative random error

The systematic errors in each individual sorption test include the uncertainty

- in the chamber volume estimations B_{r-V} ($\pm 1.3\%$),
- in the flow rate measurement B_{r-Q} ($\pm 5.0\%$),
- in the time measurement B_{r-t} ($\pm 0.0\%$),
- due to the complete mixing assumption B_{r-mx} ($\pm 0.0\%$) and
- due to possible air leakage B_{r-leak} ($\pm 0.0\%$)

These uncertainties, seemingly random, are called systematic errors because they will cause errors on the concentration measurements in the individual sorption test. The random errors in the sorption tests are uncertainty due to possible fluctuation of the ambient conditions $P_{T,RH}$ ($\pm 0.0\%$) and uncertainty due to the tube sampling and TD-GC/FID analysis P_{r-S} (maximum $\pm 3.1\%$ for BZA). These uncertainties are called random errors because their effects on the concentration measurement are inconsistent and random (Zhang et al. 2002). Both random and systematic uncertainties will propagate in

the data analysis process and affect the final result. The propagation of uncertainties will be discussed later together with the data analysis method.

DATA ANALYSIS METHOD AND RESULTS

To analyze the raw data from the experiment, an integration method was used. It is independent of any sorption models. It employs the original definition of sorption to calculate the VOC mass adsorbed per unit surface area in a certain period of time by a specimen. By comparing different VOC amounts adsorbed under different environmental conditions, the impacts of the environmental conditions can be revealed. The following will discuss the principle of the integration method, the uncertainties in the final analysis results and the effects of different environmental conditions on the sorption process.

The Principle of the Integration Method

There are many sorption models (Zhang et al. 2002), and they use different methods to analyze the data. In order to obtain results independent of these sorption models, this investigation used an empirical function to fit the experimental data, and then calculated the VOC adsorbed by integrating the adsorption rate over the period interested. This method is therefore called the integration method. Figure 5. shows the schematic of the integration method.

The integration method used the following empirical function to fit the experimental data:

$$C_{\text{normalized}}(t) = 1 - (\beta_1 e^{-\beta_2 t} + \beta_3 e^{-\beta_4 t} + \beta_5 e^{-\beta_6 t}) \quad (1)$$

The solid line in Figure 5 is the empirical function curve used to fit the experimental data. The dotted line is the uncertainty of the empirical function curve (best-fit curve). The VOCs adsorbed per unit material surface area at time, t , in the adsorption period, $M_a(t)$, can be determined by:

$$M_a(t) = \frac{\int_0^t (C_{\text{no-sink}}(t) - C(t))Qdt}{A} = \frac{C_{\text{inlet}} \cdot NV}{A} \int_0^t (1 - e^{-Nt} - C_{\text{normalized}}(t))dt \quad (2)$$

Since the air change rate $N=1$ (h^{-1}) and loading factor $L=A/V=1.8$ m^2/m^3 were used for all the tests, $M_a(t)$ can be written into the following equation:

$$\frac{M_a(t)}{C_{\text{inlet}}} = \frac{\int_0^t (1 - e^{-Nt} - C_{\text{normalized}}(t))dt}{L} = \frac{t + e^{-t} - 1 - \int_0^t C_{\text{normalized}}(t)dt}{1.8} \quad (3)$$

If we define $M_{\text{na}}(t) = \frac{M_a(t)}{C_{\text{inlet}}}$ to represent the normal amount of VOC adsorbed per unit surface area during the adsorption period, $M_{\text{na}}(t)$ is the sorption constant at t , k_t :

$$k_t = \frac{M_a(t)}{C_{inlet}} = M_{na}(t) = \frac{t + e^{-t} - 1 - \int_0^t C_{normalized}(t)dt}{1.8} \quad (4)$$

According to Equations (1) and (4), the normal VOC amount adsorbed per unit surface area during the adsorption period $M_{na}(t)$ was calculated for the six test VOCs and the three test materials (t equals to 72 hrs for painted drywall and ceiling tile, and 168 hrs for carpet). Then, by comparing the $M_{na}(t)$ values of different VOCs, different materials and different environmental conditions, the impacts of different VOCs, different materials and different environmental conditions can be revealed.

Error Analysis for $M_{na}(t)$

Before using the information from $M_{na}(t)$ to draw any conclusions regarding the impacts of the environmental conditions on the sorption process, we must analyze the uncertainties of the calculated $M_{na}(t)$. The following section discusses the uncertainties, including that of the inlet concentration, of averaging the inlet concentration, of the exhaust concentration, of the best-fit concentration curve, of the normalized best-fit curve, and that of the integrated normalized mass adsorbed per unit surface area during the sorption period. The basic theory of uncertainty propagation used here is from Coleman and Steele (1999).

a) Uncertainty of the inlet concentration ($P_{r-C_{inlet}}$):

$$P_{r-C_{inlet}} = \sqrt{\frac{\sum_{i=1}^{n_{inlet}} \left(\frac{C_{inlet}(i) - \bar{C}_{inlet}}{\bar{C}_{inlet}} \right)^2}{n_{inlet} - 1}} \quad (5)$$

where n_{inlet} is the number of samples at the chamber inlet.

b) Uncertainty of averaging the inlet concentration ($P_{r-\bar{C}_{inlet}}$):

$$P_{r-\bar{C}_{inlet}} = \frac{P_{r-C_{inlet}}}{\sqrt{n_{inlet}}} \quad (6)$$

c) Uncertainty of the exhaust concentrations ($P_{r-C(t)}$):

$$P_{r-C(t)} = \sqrt{\frac{\sum_{i=1}^n \left(\frac{C_{mi} - C_{pi}}{C_{mi}} \right)^2}{n - 1}} \quad (7)$$

where C_{mi} and C_{pi} represent the i^{th} VOC concentration measured and the corresponding concentration predicted by the best-fit curve.

d) Uncertainty of the best-fit exhaust concentration curve ($P_{r-\bar{C}(t)}$):

$$P_{r-\bar{C}(t)} = \frac{P_{r-C(t)}}{\sqrt{n}} \quad (8)$$

where n is the number of samples at the chamber exhaust.

e) Uncertainty of the normalized best-fit curve ($P_{r-\bar{C}_n(t)}$):

$$P_{r-\bar{C}_n(t)} = \sqrt{\left(P_{r-\bar{C}(t)}\right)^2 + \left(P_{r-\bar{C}_{inlet}}\right)^2} \quad (9)$$

With the above information, the uncertainty of the $M_{na}(t)$ value ($U_{M_{na}(t)}$) can be calculated as (Zhang 2001):

$$U_{M_{na}(t)} = \frac{1}{1.8} \sqrt{\left(B \int_0^t \bar{C}_n(t) dt\right)^2 + \left(P \int_0^t \bar{C}_n(t) dt\right)^2} \quad (10)$$

where,

$$\text{systematic error: } B \int_0^t \bar{C}_n(t) dt = \pm 5.2\% \quad (11)$$

$$\text{random error: } P \int_0^t \bar{C}_n(t) dt = P_{r-\bar{C}_n(t)} \int_0^t \bar{C}_n(t) dt = P_{r-\bar{C}_n(t)} \cdot (t + e^{-t} - 1 - 1.8M_{na}(t)) \quad (12)$$

Method to Determine the Effects of Environmental Conditions on VOC Sorption

If there were no uncertainties associated with calculated $M_{na}(t)$ value, it would be straightforward to justify how different conditions affect VOC sorption according to $M_{na}(t)$ value. With uncertainties involved, statistical method should be used to make the justification. Assume that $M_{na1}(t)$ and $M_{na2}(t)$ are the amounts of VOCs adsorbed under two different environmental conditions and $U_{M_{na1}(t)}$ and $U_{M_{na2}(t)}$ the corresponding uncertainties. According to Coleman and Steele (1999), to determine whether the effects of the environmental conditions are significant or not (with 95% confidence), we can compare the difference $D_{M_{na}(t)}$ ($= M_{na1}(t) - M_{na2}(t)$) between any two different environmental conditions with two times standard deviation of $D_{M_{na}(t)}$

($= U_{M_{na1}(t)-M_{na2}(t)} = \sqrt{\left(U_{M_{na1}(t)}\right)^2 + \left(U_{M_{na2}(t)}\right)^2}$). If the difference $D_{M_{na}(t)}$ is larger than $2U_{D_{M_{na}(t)}}$, we can say with 95% confidence that the difference is significant.

Otherwise, the difference is insignificant and is within measurement uncertainty. The following section will analyze the effects of environmental conditions by using $2U_{D_{M_{na}(t)}}$ as the criterion.

RESULTS AND DISCUSSIONS

This section will discuss the effects of relative humidity, temperature, and air velocity on VOC sorption of each material.

The effects of relative humidity

Painted drywall: Table 3 lists $M_{na}(72)$ for painted drywall under different humidity conditions and the uncertainties. The results indicate that the effect of relative humidity on absorption is generally small, and mostly within the experimental uncertainties. However, the impact from the low humidity condition (25%) and that from the reference humidity condition (50%) is considerable for most compounds except ethylbenzene (EB) and benzaldehyde (BZA).

Ceiling tile: The sink strength of benzaldehyde increases significantly from 50% RH to 80% RH (Table 4). It is possible that under a high humidity condition, the ceiling tile reacted with moisture and caused the sorption strength of benzaldehyde to increase (the specimen also slightly changed color after the high humidity test). However, for dodecane (DOD), $M_{na}(72)$ decreased slightly with the increase of humidity. For all the other compounds, the effects of relative humidity on the sorption of VOCs by the ceiling tile seemed to be within the experimental uncertainties.

Carpeting: Table 5 shows that the effect of relative humidity on the sink strength is insignificant for almost all the compounds except for 1,4-dichlorobenzene (DCB). The M_{na} for DCB increased slightly when the relative humidity changed from 25% to 50%.

Effects of temperature

Painted drywall: Taking into consideration that the sink strength of the painted drywall is very small itself when compared to the experimental uncertainties, the effect of temperature on the sorption strength is negligible for all the VOCs except for 1,4-dichlorobenzene (Table 6).

Ceiling tile: For the ceiling tile, Table 7 shows that the sink strength of decane, undecane, and dodecane decreases with a temperature increase, which is consistent with that the observations from Tichenor et al. (1991). For other compounds, though the $M_{na}(72)$ showed a decreasing sink effect with an increase of temperature, the effect is not evident compared to the experimental uncertainties. (The sink strength of ethylbenzene at a low temperature condition was at the same level as that in the empty chamber test, and thus its increase with the temperature might not be considered to be reliable.)

Carpeting: Table 8 shows that $M_{na}(168)$ increased with a temperature increase from 10.5°C and 23°C, while $M_{na}(168)$ decreased when the temperature increased further from 23°C to 35°C. However due to the experimental uncertainty and the limitations on the current tests, the temperature effect on this range seemed to be evident only for ethylbenzene, 1,4-dichlorobenzene, and dodecane. The sorption effect increases with an increase of temperature that is different from the results from Tichenor et al. (1991). In addition, the inconsistent temperature effect at different temperature ranges is difficult to explain using previously known theories. By using the diffusion model, Zhang (2001)

found that the partition coefficient usually decreases with the increase of temperature, while the diffusion coefficient usually increases with the increase of temperature. The combination of these two factors may have produced a peak amount of VOCs adsorbed around 23°C during the testing period.

Effects of velocity

Painted drywall: Due to the small sink strength of the painted drywall and the relatively large experimental uncertainties, the velocity effect is small for all the VOCs, though the $M_{na}(72)$ for almost all the tested VOCs seemed to decrease under the high velocity condition, as shown in Table 9.

Ceiling tile: Table 10 shows that the effects of air velocity is again very small for all tested compounds, except that a higher air velocity slightly decreased the sink strength of dodecane. The higher velocity over the ceiling tile may have disturbed the dodecane trapped in the “air pockets” of the ceiling tile so that less VOCs were adsorbed by the material.

Carpeting: According to Table 11, the $M_{na}(168)$ for most of the VOCs on the carpet decreased with the increase of air velocity. The trend was similar to that observed for the painted drywall and the ceiling tile. However, dodecane was an exception. Its sink strength increased with the increase of air velocity. A possible reason is that a higher air velocity decreased the thickness of the boundary layer and thereby increased the mass transfer of dodecane across the boundary layer, resulting in the increase of dodecane adsorbed. This explanation was verified using the diffusion model (Zhang 2001)

CONCLUSIONS

This investigation studied experimentally the effect of environmental conditions, such as relative humidity, temperature, and air velocity, on six different kinds of VOC sorption by three different materials (painted drywall, ceiling tiles, and carpeting).

For the painted drywall, the sink effect is small compared to the experimental uncertainties associated with the small-scale chamber test method. The effects of the environmental conditions were deemed insignificant with a 95% confidence level, except for a few cases, e.g. 1,4-dichlorobenzene showed a slight increase in the sorption strength when the temperature increased.

For the ceiling tile, the environmental conditions had some effects on the sorption. The impacts of relative humidity conditions are inconsistent among different VOCs, e.g., the sink strength of benzaldehyde increased with the increase of relative humidity, while the sink strength of dodecane decreased with the increase of relative humidity. With an increase of temperature, the sink strength for most VOCs, especially for alkane VOCs, decreased. The effects of air velocity were insignificant for all tested VOCs, except that a higher air velocity slightly decreased the sink strength of dodecane.

For the carpeting, the sink strength increased with an increase of temperature from 10.5°C to 23°C, while it decreased with an increase of temperature from 23°C to 35°C, for most of the VOCs. This inconsistency of the temperature effect was different from previous research results, but it can be explained by using the diffusion model. In addition, the higher relative humidity condition appeared to decrease the sink strength of dodecane on carpet while it showed no major effect on other VOCs. A higher velocity decreased the sink strength of 1,4-dichlorobenzene while it increased the sink strength of dodecane.

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Table 1. Physicochemical properties of tested VOCs

VOCs	Molecular formula	Molecular weight	Boiling point (°C)	Vapor Pressure, p_0^1 (mmHg)
Ethylbenzene	C ₈ H ₁₀	106	136.2	8.27
1,4-dichlorobenzene	C ₆ H ₄ Cl ₂	147	173	1.41
Decane	C ₁₀ H ₂₂	142	174.1	1.89
Benzaldehyde	C ₇ H ₆ O	106	178	1.06
Undecane	C ₁₁ H ₂₂	156	195.9	0.68
Dodecane	C ₁₂ H ₂₆	170	216	0.25

¹Lide 1995 and Meylan and Howard 1996

Table 2. Test Conditions for Each Material*

Test No.	Temperature (°C)	Relative Humidity (%)	Air Velocity (m/s)	Test purpose
1	23	50	0.05	Reference test condition
2	35	50	0.05	High temperature condition
3	10.5	50	0.05	Low temperature condition
4	23	25	0.05	Low relative humidity condition
5	23	80	0.05	High relative humidity condition
6	23	50	0.62	High velocity

* One air change per hour flow rate was used for all the tests.

Table 3. The effect of relative humidity on $M_{na}(72)$ for the painted drywall

	Low RH	Ref. RH	High RH	$2U_{RH_{LR}}^*$	$2U_{RH_{RH}}$	$2U_{RH_{LH}}$	Eff. _{LR}	Eff. _{RH}	Eff. _{LH}
EB	0.816	0.820	0.934	0.644	0.684	0.506	~	~	~
BZA	2.715	2.146	2.840	1.639	1.376	1.303	~	~	~
DEC	0.605	1.430	1.370	0.845	0.734	0.721	~	~	↑
DCB	1.519	1.977	2.359	0.759	0.744	0.568	~	~	↑
UND	1.168	1.887	1.984	0.873	0.684	0.636	~	~	↑
DOD	1.935	2.619	2.748	0.687	0.563	0.484	~	~	↑

* $2U_{RH_{LR}}$ means the $2U_{M_{na1}(t)-M_{na2}(t)}$ for the low relative humidity condition and reference condition (L means low, R means reference, H means High)

Table 4. The effect of relative humidity on $M_{na}(72)$ for the ceiling tile

	Low RH	Ref. RH	High RH	$2U_{RH_{LR}}$	$2U_{RH_{RH}}$	$2U_{RH_{LH}}$	Eff. _{LR}	Eff. _{RH}	Eff. _{LH}
EB	0.501	0.534	0.630	0.509	0.689	0.530	~	~	~
BZA	4.779	4.619	9.781	1.297	1.341	1.250	~	↑	↑
DEC	1.024	1.032	0.802	0.593	0.822	0.475	~	~	~
DCB	1.710	1.458	2.228	0.561	0.839	0.619	~	~	~
UND	2.868	2.633	2.779	0.638	0.977	0.536	~	~	~
DOD	6.548	5.944	5.242	0.789	1.139	0.545	~	~	↓

Table 5. The effect of relative humidity on $M_{na}(168)$ for the carpeting

	Low RH	Ref. RH	High RH	$2U_{RH_{LR}}$	$2U_{RH_{RH}}$	$2U_{RH_{LH}}$	Eff. _{LR}	Eff. _{RH}	Eff. _{LH}
EB	4.156	4.463	4.706	1.139	1.356	2.230	~	~	~
BZA	15.428	14.203	11.545	3.691	3.768	4.365	~	~	~
DEC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DCB	13.974	15.045	15.510	1.027	1.132	2.226	↑	~	~
UND	18.156	N/A	19.693	N/A	N/A	2.088	N/A	N/A	~
DOD	32.466	32.513	32.515	0.920	0.998	1.893	~	~	~

N/A means not available, because the compound was not tested under that condition.

Table 6. The effect of temperature on $M_{na}(72)$ for the painted drywall

	Low T	Ref. T	Hi. T	$2U_{T_{LR}}$ *	$2U_{T_{RH}}$	$2U_{T_{LH}}$	Eff. _{LR}	Eff. _{RH}	Eff. _{LH}
EB	0.470	0.820	0.929	0.699	0.506	0.621	~	~	~
BZA	2.462	2.146	2.549	1.579	1.303	1.298	~	~	~
DEC	1.056	1.430	1.367	0.746	0.721	0.471	~	~	~
DCB	1.153	1.977	2.045	0.896	0.568	0.811	~	~	↑
UND	1.641	1.887	1.751	0.812	0.636	0.685	~	~	~
DOD	2.707	2.619	2.532	0.642	0.484	0.590	~	~	~

* $2U_{T_{LR}}$ means the $2U_{M_{na1}(t)-M_{na2}(t)}$ for the low temperature condition and the reference condition (L means low, R means reference, and H means High)

Table 7. The effects of temperature on $M_{na}(72)$ for the ceiling tile

	Low T	Ref.	Hi. T	$2U_{T_{LR}}^*$	$2U_{T_{RH}}$	$2U_{T_{LH}}$	Eff.LR	Eff.RH	Eff.LH
EB	0.098	0.534	0.511	0.582	0.530	0.486	~	~	~
BZA	5.858	4.619	4.010	2.753	1.250	2.649	~	~	~
DEC	1.428	1.032	0.426	0.658	0.475	0.568	~	↓	↓
DCB	2.029	1.458	1.399	0.816	0.619	0.842	~	~	~
UND	4.394	2.633	1.822	0.651	0.536	0.530	↓	↓	↓
DOD	10.901	5.944	3.807	0.608	0.545	0.548	↓	↓	↓

Table 8. The effects of temperature on $M_{na}(168)$ for the carpeting

	Low T	Ref. T	High T	$2U_{T_{LR}}^*$	$2U_{T_{RH}}$	$2U_{T_{LH}}$	Eff.LR	Eff.RH	Eff.LH
EB	1.795	4.463	3.923	1.545	2.230	2.333	↑	~	~
BZA	12.989	14.203	9.093	4.231	4.365	3.775	~	~	↓
DEC	4.186	N/A	7.086	N/A	N/A	2.552	N/A	N/A	↑
DCB	12.940	15.045	9.058	1.035	2.226	2.202	↑	↓	↓
UND	9.857	N/A	15.737	N/A	N/A	2.361	N/A	N/A	↑
DOD	22.712	32.513	26.791	1.122	1.893	1.964	↑	↓	↑

Table 9. The effect of air velocity on $M_{na}(72)$ for the painted drywall

	Ref.	Hi. V	$2U_{V_{RH}}^*$	Eff.v
EB	0.820	0.558	0.694	~
BZA	2.146	2.193	1.366	~
DEC	1.430	0.901	0.832	~
DCB	1.977	1.893	0.763	~
UND	1.887	1.443	0.881	~
DOD	2.619	2.250	0.608	~

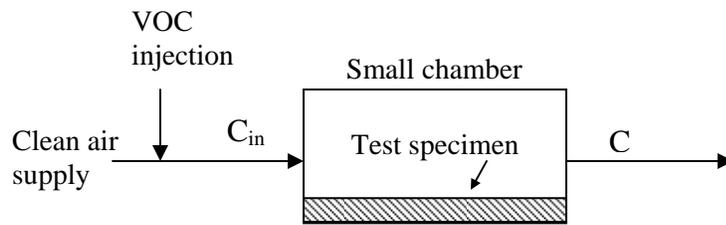
* $2U_{V_{RH}}$ means the $2U_{M_{na1}(t)-M_{na2}(t)}$ for the reference and high velocity condition (R means reference, and H means High)

Table 10. The effect of air velocity on $M_{na}(72)$ for the ceiling tile

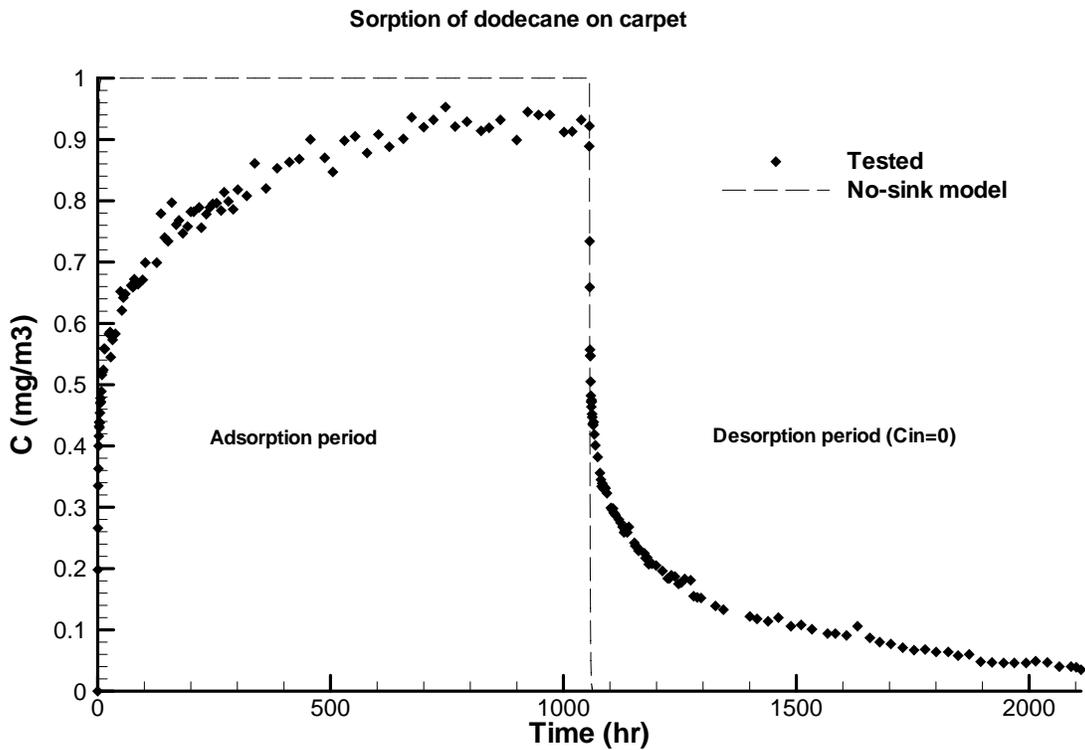
	Ref.	Hi. V	$2U_{v_{RH}}$	Eff.v
EB	0.534	0.521	0.599	~
BZA	4.619	5.784	1.333	~
DEC	1.032	0.777	0.546	~
DCB	1.458	1.564	0.611	~
UND	2.633	2.071	0.712	~
DOD	5.944	4.983	0.637	↓

Table 11. The effects of air velocity on $M_{na}(168)$ for the carpeting

	Ref.	Hi. V	$2U_{v_{RH}}$	Eff.v
EB	4.463	3.157	1.484	~
BZA	14.203	12.387	3.787	~
DEC	N/A	N/A	N/A	N/A
DCB	15.045	11.907	1.090	↓
UND	N/A	18.479	N/A	N/A
DOD	32.513	35.296	1.129	↑



(a) Schematic of the experimental setup



(b) Example data from the experiment

Figure 1. Principle of sorption test using a small environmental chamber: difference between the measured and tested concentration at exhaust reveals the adsorption and desorption by the test specimen

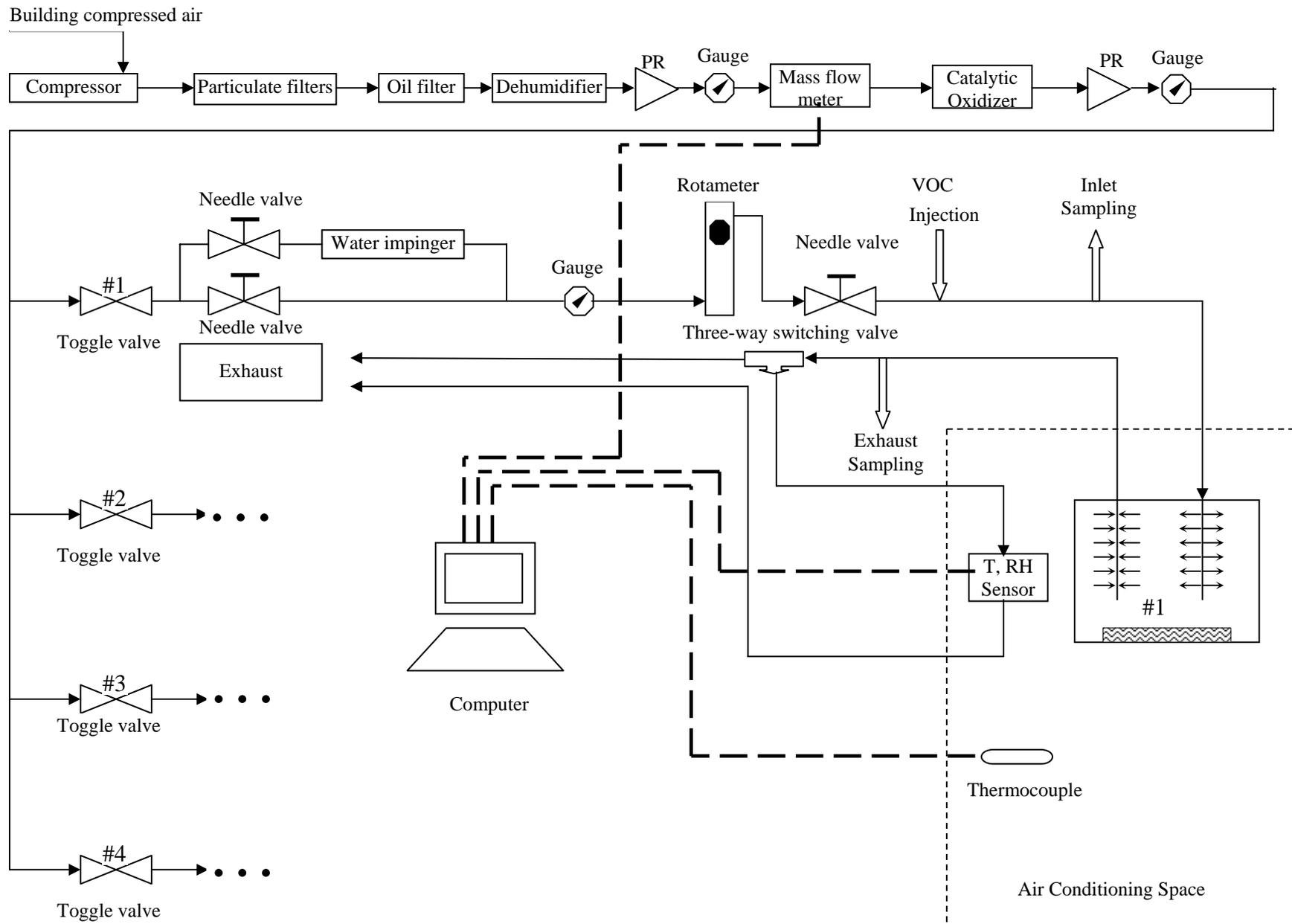


Figure 2. Schematic of the small-scale chamber sorption test system

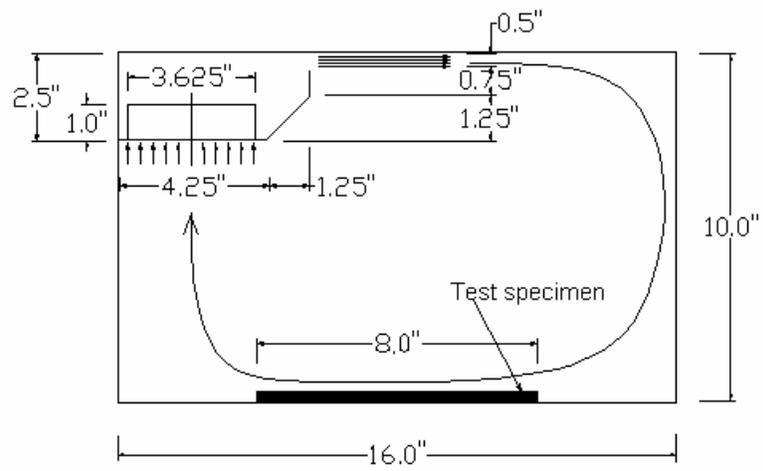


Figure 3. The design of velocity controlled test chamber

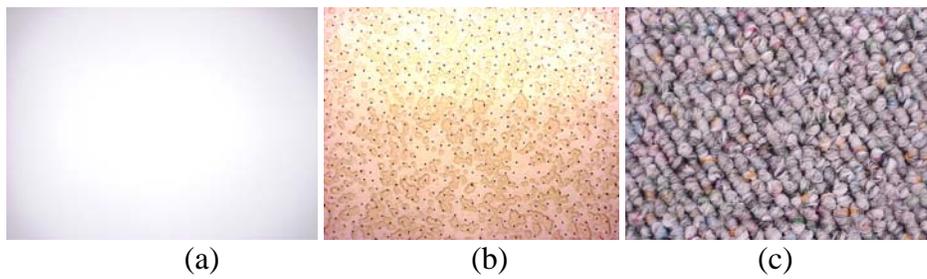


Figure 4. The design of velocity controlled test chamber; (a) painted drywall, (b) ceiling tile, and (c) carpet

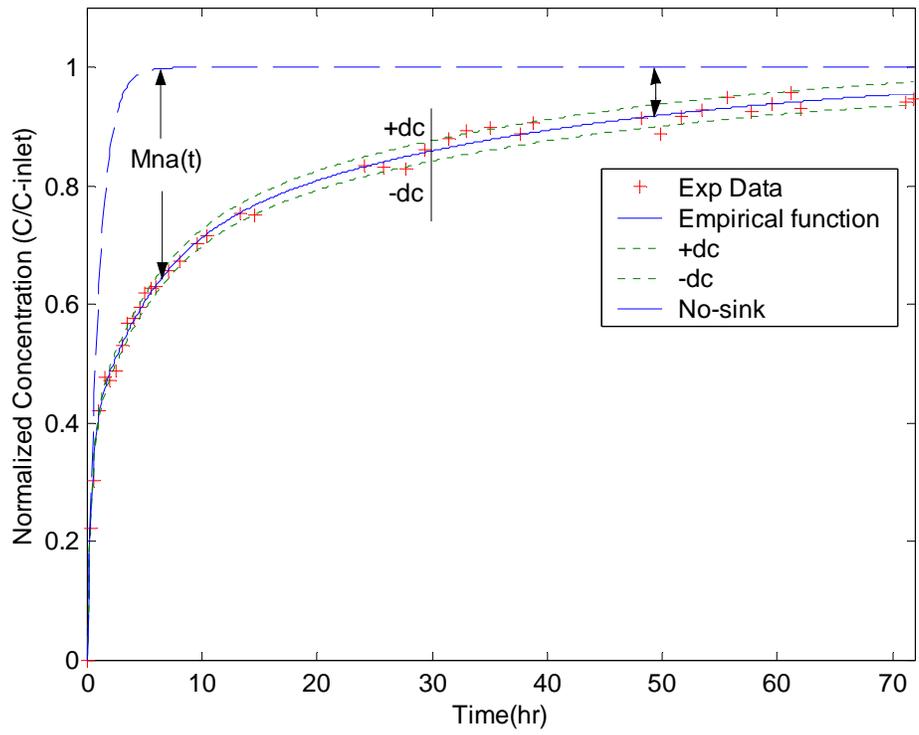


Figure 5. Schematic of the integration method