



Evaluation of impact factors on VOC emissions and concentrations from wooden flooring based on chamber tests

Chi-Chi Lin^{a,*}, Kuo-Pin Yu^b, Ping Zhao^c, Grace Whei-May Lee^d

^a Department of Civil and Environmental Engineering, National University of Kaohsiung, No. 700, Kaohsiung University Rd., Kaohsiung, Taiwan, ROC

^b Institute of Environmental and Occupational Health Sciences, National Yang-Ming University, No.155, Sec.2, Linong Street, Taipei, Taiwan, ROC

^c Filtration Group Inc., 912 E. Washington Street, Joliet, IL 60433, USA

^d Graduate Institute of Environmental Engineering, National Taiwan University, 71, Chou-Shan Rd., Taipei, Taiwan, ROC

ARTICLE INFO

Article history:

Received 4 September 2007

Received in revised form

22 April 2008

Accepted 23 April 2008

Keywords:

Wooden flooring

Temperature

Relative humidity

Air exchange rate

Environmental test chamber

ABSTRACT

In this study, the impact factors of temperature, relative humidity (RH), air exchange rate, and volatile organic compound (VOC) properties on the VOC (toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene) specific emission rates (SERs) and concentrations from wooden flooring were investigated by chamber test for 8 days. The tested wood in this study is not common solid wood, but composite wood made of combined wood fibers. The experiments were conducted in a stainless-steel environmental test chamber coated with Teflon. The experimental results within 8 days of testing showed that, when the temperature increased from 15 to 30 °C, the VOC SERs and concentrations increased 1.5–129 times. When the RH increased from 50% to 80%, the VOC concentrations and SERs increased 1–32 times. When the air change rate increased from 1 to 2 h⁻¹, the VOC concentrations decreased 9–40%, while the VOC SERs increased 6–98%. The relations between the boiling points of the VOCs and each of the normalized VOC SERs and concentrations were linear with negative slopes. The relations between the vapor pressures of the VOCs and each of the normalized VOC SERs and concentrations were linear with positive slopes. At 15 °C, RH50%, the relations between the diffusivities of VOCs and each of the normalized VOC equilibrium SERs and concentrations were linear with a positive slope.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

The volatile organic compounds (VOCs) emitted from building materials have been recognized as pollutants that may deteriorate indoor air quality in terms of odor annoyance, and eye and airway irritation, which may be related to the sick building syndrome [1–5]. Some studies have shown that air temperature and humidity have a strong impact on the perception of air quality or VOC emissions from building materials [4,6–9].

Wolkoff [4,7] measured the time course emissions of VOCs from five building materials (carpet, PVC flooring, sealant, water-borne wall paint, and floor varnish). After ventilation of the materials for 1 week, most of the VOC emissions increased when the temperature increased. Increasing the relative humidity (RH) by 50% was seen to increase the emission of VOCs emitted from carpet, sealant, and wall paint. However, after being ventilated for 3 weeks, most of the VOC emissions from the materials were independent of air temperature and humidity. Overall, the effect

of temperature and RH depended strongly on the type of building products and type of VOCs. A strong impact of temperature and humidity on the emission of formaldehyde from chipboard was observed by Andersen et al. [9]. They found that within the temperature range 14–35 °C, the chemical emission rate of formaldehyde was doubled for each 7 °C temperature rise. Also, the emission rate was doubled when the relative air humidity increased from 30% to 70% at 22 °C. Sollinger et al. [10] studied the impact of temperature and humidity on the VOC emission from textile floor coverings by determining equilibrium concentrations (zero air change) at elevated temperatures in the range 23–71 °C and at a RH of 0% and 45%. They found that emission of the relative volatile compounds such as styrene showed little dependence on temperature. Strong temperature dependence was found for the emission of low-volatility compounds such as benzothiazol. However, the emission of all VOCs identified in the experiment was found to be independent of temperature in the typical indoor temperature range 23–30 °C. The effect of RH on VOC emission from the carpet tested was found to be negligible, except for aniline.

Air velocity impact of VOC emission was also studied by some researchers. Wolkoff [7] showed that primary source emissions

* Corresponding author. Tel.: +886 7 5919378.

E-mail address: chichilin@nuk.edu.tw (C.-C. Lin).

were not affected by air velocity after a few days to a large extent. The primary VOC emissions from most building products were shown to be independent of air velocity, while increased air velocity may result in increased secondary VOC emissions if the building product surface is sensitive to oxidative degradation [11].

The objective of this study is to investigate the effects of temperature, RH, and air change rate on the VOC specific emission rates (SERs) and concentrations from wooden flooring, one of the common building materials for interior decoration. The relations between the VOC SERs and concentrations and the properties of VOCs were also studied. The VOC emission experiments were conducted in an environmental test chamber. The double-exponential model developed by Colombo et al. [12] was selectively picked to fit the observed VOC concentration–time profiles. The results could be used to predict VOC SERs and concentrations and evaluate the occupant exposure to VOCs.

2. Experimental methods

2.1. Materials

The wooden flooring tested was hardwood plywood provided by a local manufacturer. The dimensions of the wooden flooring specimen were 11 cm × 11 cm × 1.2 cm. Before the experiments, the wooden flooring was wrapped in aluminum foil and stored in a 4 °C refrigerator for storage. We got the specimens right after they were produced. They were stored up to 3 months before testing.

2.2. Methods

The wooden flooring specimen was cut into small pieces and then ground into powder. The powder was collected in a 1-L glass vessel; then the vessel was purged with 0.5 L/min of nitrogen gas (purity = 99.9%). The headspace gas effluent was analyzed by GC–MS (Finnigan Mat GCQ Mass Spectrometer, with an HP-1 capillary column Rtx-624, 60 m × 0.25 mm ID, 1.00 μm film). According to the GC–MS analysis results, toluene (content percentage = 2.79%), m,p-xylene (content percentage = 8.51%), ethylbenzene (content percentage = 9.44%), 2-ethylhexyl acrylate (content percentage = 31.3%), and n-butyl acetate (content percentage = 44.7%) were the dominate VOC species. Thus, we selected these five VOC species as target compounds. These selected VOCs are not typical for untreated solid soft or hard wood. The reason is probably that the tested wood in this study is not common solid wood, but composite wood made of combined wood fibers.

The experiments were conducted in a 40 cm × 40 cm × 35 cm stainless-steel environmental test chamber with Teflon coated all over inner walls in order to minimize VOC interaction with chamber walls so that VOC loss on the wall was assumed to be negligible in data analysis later on (Fig. 1). The test chamber was checked thoroughly and no leakage was found. Moreover, the difference in flow rate between the inlet and the outlet was insignificant; hence, the VOC loss by leakage could be ignored. There was no recovery test carried out. One wooden flooring specimen was placed on the middle of the chamber floor. Supply air for the test chamber was provided by an air compressor and the VOCs, humidity, and particle matter in the supply air were removed by an active carbon filter, a diffusion silicate dryer, and an HEPA filter, respectively. The temperature of the chamber was maintained at 15 °C (or 25 or 30 ± 1 °C) by a thermostatic chamber (DENG TNG Instruments Co., Ltd). The RH of the chamber was

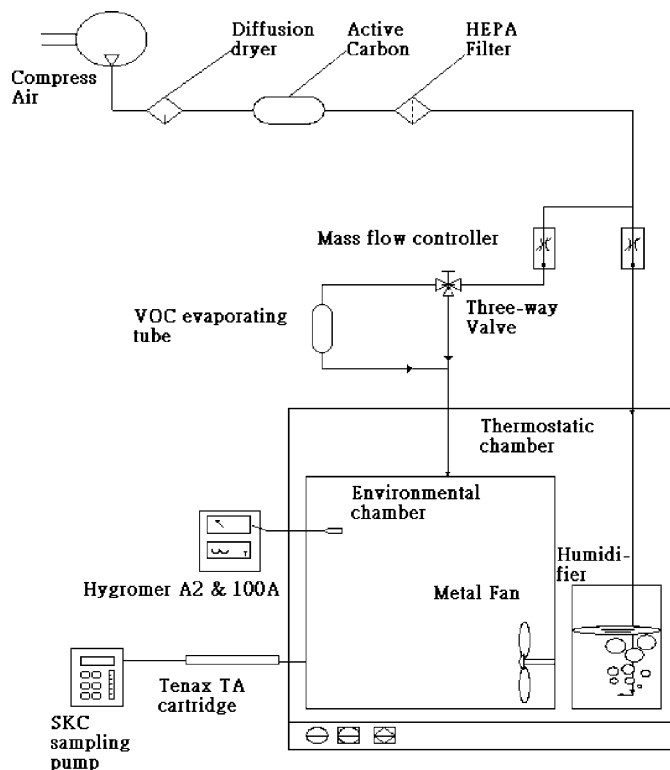


Fig. 1. Small-scale environmental chamber.

controlled at 50% (or 80%) by adjusting the air flow rate passing through the humidifier. The air exchange rate through the chamber was controlled at 1 h⁻¹ (or 2 h⁻¹) by electronic mass flow controllers (SIERRA Instruments, INC). A metal fan was installed in the chamber for mixing air. CO₂ gas was used as a gaseous tracer and the CO₂ concentration was monitored by Q-Trak (TSI, 8550). The mixing level determination was based on the ASTM D5116-97 standard practice [13] as follows:

$$\eta = \left\{ 1 - \frac{\sum_{i=1}^n [C_{tr}(t_i) - C_{th}(t_i)](t_i - t_{i-1})}{\sum_{i=1}^n [C(t_i)(t_i - t_{i-1})]} \right\} \times 100\% \quad (1)$$

where η is the mixing level (%), t_i the elapsed time of the i th sample (h), n the serial number of the sample, $C_{tr}(t_i)$ (ppm) the CO₂ concentration in the outlet at t_i , and $C_{th}(t_i)$ (ppm) the theoretical CO₂ concentration under completely mixing condition, calculated by the following equation:

$$C_{th}(t_i) = C_{tr}(0) e^{-ACH t} \quad (2)$$

where $C_{tr}(0)$ is the initial CO₂ concentration (~6000 ppm), and ACH is the air exchange rate (h⁻¹). The mixing level of each experiment was maintained above 80%.

The VOC sampling device included 500-mg Tenax TA (60/80 mesh) cartridges (SUPELCO) and sampling pump (SKC). The sampling flow rate was 30 mL/min and sampling time varied from 10 min during the first day to 30 min after 4 day of sampling. Immediately after sample collection, the Tenax TA cartridges were thermal desorbed and cryofocused by TEKMAR 6000 Aero Trap Desorber and then injected into the GC column and analyzed by the flame ionization detector (FID; HP5890 series II, with HP-1 capillary column SPB-5, 30 m × 0.53 mm ID, 0.5 μm film, SUPELCO).

The quantification was conducted as the following. First, 1 μL of TO 1 (toxic organic mixture, SUPELCO) reference solution was injected into a 125-mL glass sampling bulk (SUPELCO). After the

reference solution was evaporated, the air in the sampling bulk was flushed out with compressed air of 50% or 80% RH at a flow rate of 25 mL/min and the tail gas was sampled on a Tenax TA cartridge for 30 min and then analyzed by the GC system. In order to eliminate the impact of water vapor on analysis results, calibration curves under different RH conditions were created based on the analytic results of a series of reference solutions of VOC. The detection limit was determined according to the USEPA MDL (The US Environmental Protection Agency's method detection limit) procedure and the detection limits for toluene, *n*-butyl acetate, ethylbenzene, *m,p*-xylene, and 2-ethylhexyl acrylate were 0.039, 0.065, 0.096, 0.076, and 0.053 ng, respectively. All the experimental results in this study were repeatable ($n = 3$) and the precision was good (relative error <2.92%).

2.3. Data analysis

Assuming that the inlet VOC concentration and the sink effect of the chamber are negligible, the mass balance of the chamber can be expressed as the following equation:

$$V \frac{dC(t)}{dt} = AE(t) - QC(t) \quad (3)$$

where V (m^3) is the chamber volume, $C(t)$ ($\mu\text{g}/\text{m}^3$) the average VOC concentration in the chamber, A (m^2) the surface area of the wooden flooring specimen, and Q (m^3/h) the air flow rate passing through the chamber. In Eq. (3), when the differential term $dC(t)/dt$ approximates zero, $C(t)$ can be treated as the equilibrium concentration C_{eq} , and $E(t)$ as the equilibrium SER E_{eq} .

The double-exponential model proposed by Colombo et al. [12] was used to fit the data observed in the experiments. The model can be expressed as the following equation:

$$E(t) = E_1(t) + E_2(t) \\ = E_1(0) \exp(-k_1 t) + E_2(0) \exp(-k_2 t) \quad (4)$$

where $E(t)$ ($\mu\text{g}/\text{m}^2/\text{h}$) is the VOC SERs, $E_1(t)$ ($\mu\text{g}/\text{m}^2/\text{h}$) the phase-one SER, $E_2(t)$ ($\mu\text{g}/\text{m}^2/\text{h}$) the phase-two SER, $E_1(0)$ and $E_2(0)$ ($\mu\text{g}/\text{m}^2/\text{h}$) are the initial SERs of phase one and phase two, respectively, and k_1 and k_2 (h^{-1}) are the SER decay constants of phase one and phase two, respectively. Generally, $E_1(0)$ is larger than $E_2(0)$, and k_1 is larger than k_2 .

Substituting Eq. (4) into Eq. (3) and integrating (assuming initial VOC concentration was zero), we have

$$C(t) = \frac{LE_1(0)}{ACH - k_1} \exp(-k_1 t) + \frac{LE_2(0)}{ACH - k_2} \exp(-k_2 t) \\ - \left[\frac{LE_1(0)}{ACH - k_1} + \frac{LE_2(0)}{ACH - k_2} \right] \exp(-ACH t) \quad (5)$$

where L is the loading factor, which equals A/V , and ACH equals Q/V . We used Eq. (5) to fit the VOC concentration–time profile observed in this study.

The accumulated VOC emission E_{ac} from the wooden flooring was calculated by the following equation:

$$E_{\text{ac}}(t) = \int_{t=0}^t E(t) dt = C(t)V + \int_{t=0}^t C(t)Q dt \quad (6)$$

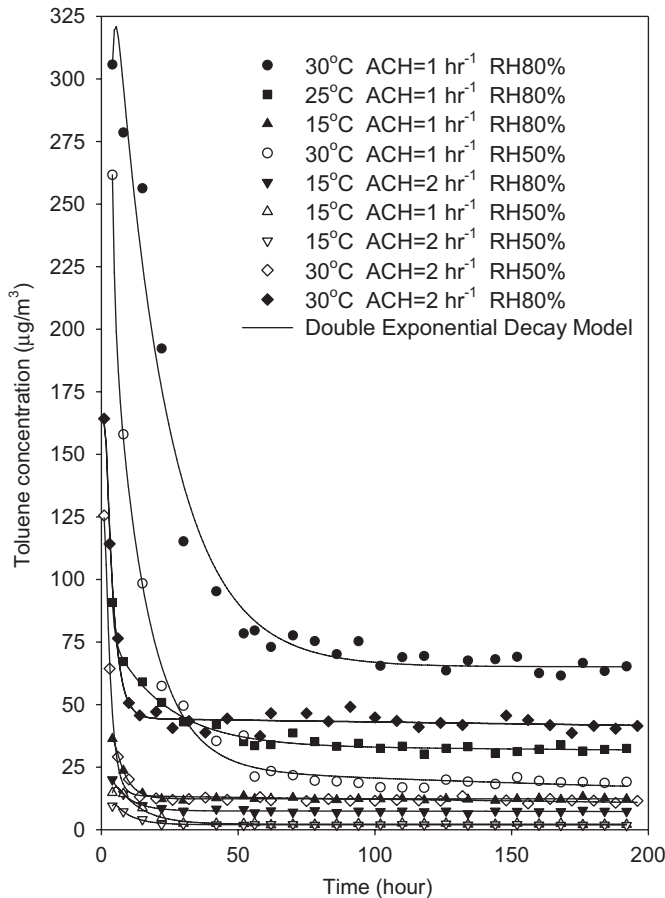


Fig. 2. Toluene concentration–time profile.

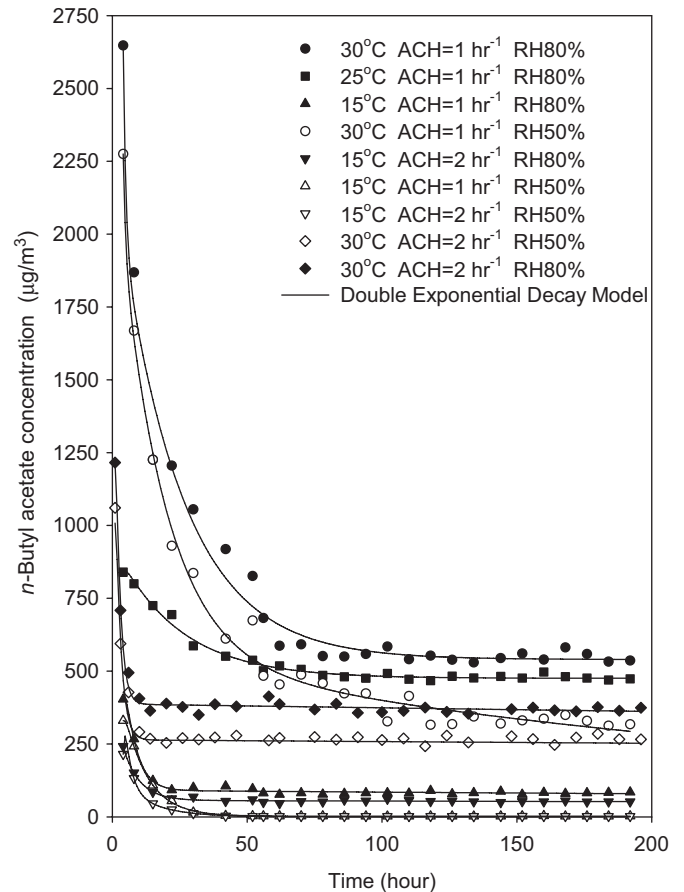


Fig. 3. Concentration–time profile of *n*-butyl acetate.

3. Results and discussion

3.1. VOC SER and concentration

Toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene concentration–time profiles and curve fitting of the double-exponential model at various temperatures, RH, and air exchange rates are shown in Figs. 2–5, respectively. But no 2-ethylhexyl acrylate emission from the wooden flooring was observed. The data presented in Figs. 2–5 are the average value based on triple experiments and the varieties between the different runs were within 10%. The experimental and regression results are listed in Table 1. The VOC concentrations attained maximums at around 4–6 h and reached equilibrium states at about 50-h. The initial concentration of *n*-butyl acetate (C_{int}) was the highest among all the VOCs observed. The second highest was that of toluene, and then ethylbenzene and *m,p*-xylene. The VOC equilibrium concentrations (C_{eq}) were in the same order, that is *n*-butyl acetate, toluene, ethylbenzene, and then *m,p*-xylene.

As shown in Table 1, in most cases, $E_1(0)$ is larger than $E_2(0)$ and k_1 is greater than k_2 . $E_2(t)$ is very close to the equilibrium SER, E_{eq} . Thus, when the SER achieved a steady state, $E_2(t)$ dominates the overall SER. These results agree with the assumption of the double-exponential model that $E_1(t)$ represents a higher initial SER process with a fast decay rate and corresponds to the short-term gas-phase SER. $E_2(t)$ represents a lower initial SER process with a very slow decay rate and corresponds to the long-term gas-phase SER [14].

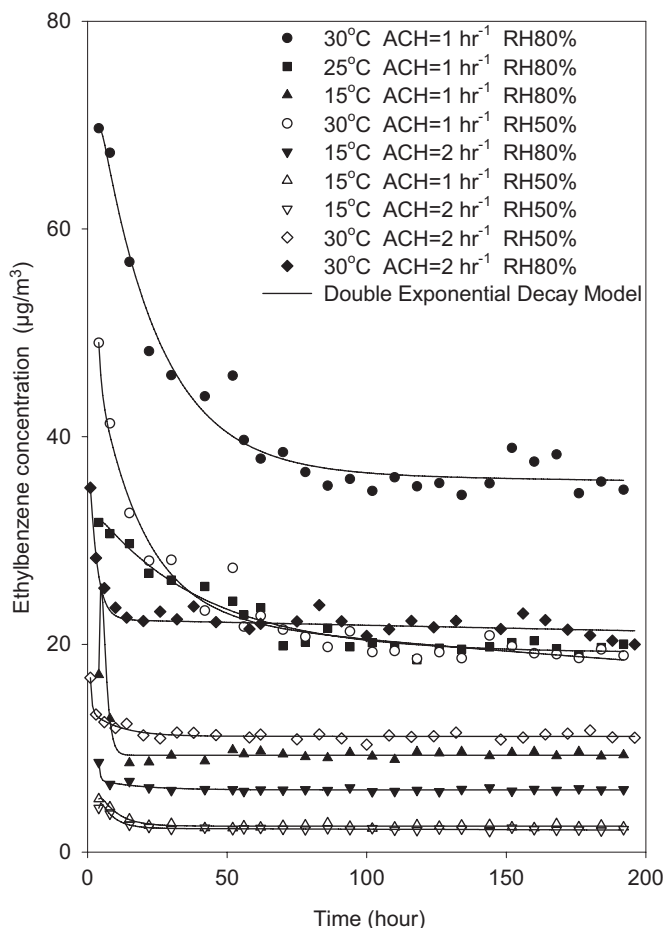


Fig. 4. Concentration–time profile of ethylbenzene.

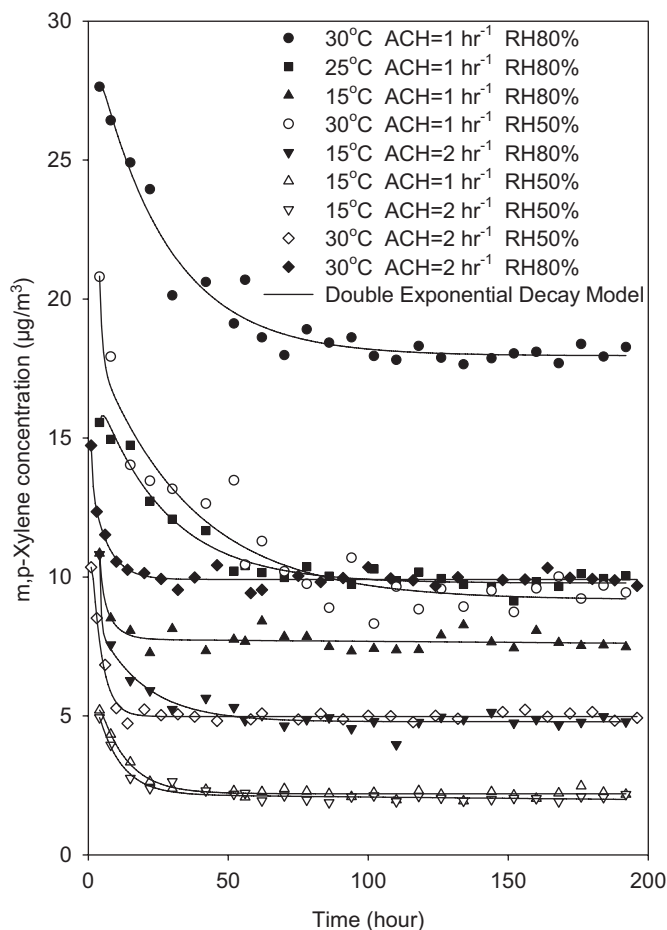


Fig. 5. Concentration–time profile of *m,p*-xylene.

3.2. Temperature

According to our experimental results, when the temperature increased from 15 to 30 °C, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene equilibrium SERs and concentrations increased 4.9–8.5, 6.4–128.8, 2.6–9.8, and 1.5–4.4 times, respectively. Meanwhile, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene initial SERs and concentrations increased 7.2–17.8, 4.2–6.9, 3.7–8.0, and 1.3–4.0 times, respectively. The enhancement effect of temperature on VOC concentrations and SERs under RH of 50% was more significant than that under RH of 80%. Therefore, increase of temperature would result in higher short- and long-term occupant exposure to VOCs, and this impact was more significant under lower RH. Dunn and Tichenor [15] suggested that temperature was the dominant factor that influences the steady-state VOC concentrations and SERs. The enhancement effect of temperature on the VOC emission may result from the positive effect of temperature on vapor pressures and diffusivities of VOCs. The temperature dependence of VOC vapor pressures can be expressed as the Antoine equation:

$$\log P = a - \frac{b}{c + T} \quad (7)$$

where P is the vapor pressure of the compound of interest (atm), T the absolute temperature (K), and a , b , and c are parameters greater than zero; $b = \Delta H_{vap}/R$, where ΔH_{vap} is the heat of vaporization, and R the gas constant.

Table 1
Summary of VOC SERs, concentrations, and SER decay constants

VOCs	RH (%)	50	50	50	50	80	80	80	80	80
	ACH (h ⁻¹)	1	1	2	2	1	1	1	2	2
	Temperature (°C)	15	30	15	30	15	25	30	15	30
Toluene	C_{int} (μg/m ³)	14.9	262	9.6	125	36.4	90.8	306	20.1	164
	C_{eq} (μg/m ³)	2.3	19.4	2.0	11.9	12.4	33.1	69.1	7.4	36.6
	E_{int} (μg/m ² /h)	38.5	685.8	52.91	725.7	111.1	194.1	694	109.5	845
	E_{eq} (μg/m ² /h)	4.3	36.6	7.5	44.9	23.4	62.5	130.4	27.9	138.1
	$E_1(0)$ (μg/m ² /h)	34.4	619	45.5	674	87.8	124	573	80.9	677.7
	$k_1 \times 10^3$ (h ⁻¹)	81	125	123	493	210	80.2	47.7	156	353
	$E_2(0)$ (μg/m ² /h)	4.1	66.8	7.41	51.7	23.3	70.1	121	28.6	168
	$k_2 \times 10^3$ (h ⁻¹)	0	4.6	0	1.1	0	0.9	0	0.2	0.3
n-Butyl acetate	C_{int} (μg/m ³)	330	2280	215	1060	404	1041	2650	242	1216
	C_{eq} (μg/m ³)	2.6	335	2.0	255	82.6	483	555	52.1	377
	E_{int} (μg/m ² /h)	886.3	5198	1291	6004	1205	2121	6120	1467	7043
	E_{eq} (μg/m ² /h)	4.9	632.1	7.5	962.3	155.8	911.3	1047	196.6	1423
	$E_1(0)$ (μg/m ² /h)	883	3942	1283	4964	1040	1150	4590	1253	5582
	$k_1 \times 10^3$ (h ⁻¹)	104	88.6	132	527	173	71.4	101	167	597
	$E_2(0)$ (μg/m ² /h)	3.3	1256	8.4	1040	165	971	1530	214	1461
	$k_2 \times 10^3$ (h ⁻¹)	0	4.7	0.7	0.2	0	0.5	3	0.4	0.3
Ethylbenzene	C_{int} (μg/m ³)	5.1	49	4.2	24	17.1	41.3	69.7	8.7	35.1
	C_{eq} (μg/m ³)	2.5	19.9	2.2	11.3	9.4	20.2	36.4	6.0	22.3
	E_{int} (μg/m ² /h)	12.49	122.9	17.31	161.6	52	103.7	144.2	59.2	182
	E_{eq} (μg/m ² /h)	4.7	37.5	8.3	42.6	17.7	38.1	68.7	22.6	84.2
	$E_1(0)$ (μg/m ² /h)	7.78	75.9	9.10	112	34.4	55.1	75.8	36.1	95
	$k_1 \times 10^3$ (h ⁻¹)	128	167	79.7	1150	268	205	45.6	388	602
	$E_2(0)$ (μg/m ² /h)	4.71	47	8.21	49.6	17.6	48.6	68.4	23.1	87
	$k_2 \times 10^3$ (h ⁻¹)	0	1.8	0	0.3	0	1.87	0.1	0.15	0.5
m,p-Xylene	C_{int} (μg/m ³)	5.2	20.8	4.9	10.4	11.8	15.6	27.6	10.8	14.7
	C_{eq} (μg/m ³)	2.2	9.6	2.0	5.1	7.7	10.0	18.3	4.8	7.4
	E_{int} (μg/m ² /h)	12.1	42.7	24	50.7	32.9	31.8	55.6	56.6	72.4
	E_{eq} (μg/m ² /h)	4.2	18.1	7.5	19.2	14.5	18.9	34.5	18.1	27.9
	$E_1(0)$ (μg/m ² /h)	8	21.3	15.8	31.9	18.2	13.4	21.7	36.8	34.4
	$k_1 \times 10^3$ (h ⁻¹)	98.4	68.9	119	321	369	38.5	39.1	168	471
	$E_2(0)$ (μg/m ² /h)	4.1	21.4	8.21	18.8	14.7	18.4	33.9	19.8	38
	$k_2 \times 10^3$ (h ⁻¹)	0	1.29	0.4	0	0.1	0	0	0.6	0.1

C_{int} : initial concentration, C_{eq} : equilibrium concentration, E_{int} : initial SER $E_{int} = E_1(0) + E_2(0)$, E_{eq} : equilibrium SER, $E_{eq} = ACH C_{eq}/L$, where L is the loading factor (see Eq. (5)).

The temperature dependence of diffusivities D_a of VOCs can be expressed as the following equation.

$$D_a = 10^{-3} \frac{T^{1.75} [(1/m_{air}) + (1/m)]^{1/2}}{P [\bar{V}_{air}^{1/3} + \bar{V}^{1/3}]^2} \quad (8)$$

where T is the absolute temperature (K), m_{air} the average molecular mass of air (28.91 g/mol), m the VOC molecular mass (g/mol), P the gas-phase pressure (atm), $\bar{V}_{air}$ the average molar volume of the gases in air (cm³/mol), and $\bar{V}$ the molar volume of the chemical of interest (cm³/mol). Xu and Zhang [16] developed a model with these parameters, including diffusivity, partition coefficient, initial concentration, convective mass transfer coefficient, and any factors that affect the four parameters would impact VOC emission and concentrations. Therefore, this agreement verifies the positive effect of temperature on VOC emissions and concentrations.

3.3. RH

According to our experimental data, when the RH increased from 50% to 80%, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene equilibrium SERs and concentrations increased 3.5–5.4, 1.1–1.4, 1.8–3.8, and 1.5–3.5 times, respectively. Meanwhile, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene initial SERs and concentrations increased 1.0–2.9, 1.7–31.8, 1.4–4.2, and

1.3–2.7 times, respectively. Therefore, the increase of RH had an enhancement effect on the VOC SERs and concentrations. The enhancement effects of RH may result from the latent heat of water vapor (or the heat of vaporization of water). The evaporation rate of water under higher RH is lower than that under lower RH. This process (evaporation of water) absorbed the heat of vaporization (40.7 kJ/mol) and retarded the VOC SERs. Under lower RH, the retardation of VOC SER was more significant than that under higher RH.

Another mechanism of the enhancement effect of RH may be due to the competition between water and the VOC molecules for the adsorption sites of wooden flooring, which in turn changes partition coefficients of VOCs between wood and air. The adsorption sites of wooden flooring can generally be categorized into two types—hydrophobic and hydrophilic ones. The VOCs are adsorbed on either the hydrophobic or hydrophilic ones, and this was relevant to the octanol/water partition coefficient K_{ow} of the VOCs. Water molecules tend to be adsorbed on the hydrophilic ones. When the RH increased, more VOCs would be desorbed from the hydrophilic adsorption sites.

3.4. Air exchange rate

In accordance with our experimental results, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene initial concentrations dropped 36–45%, 35–40% 18–49%, and 6–8%, respectively, when

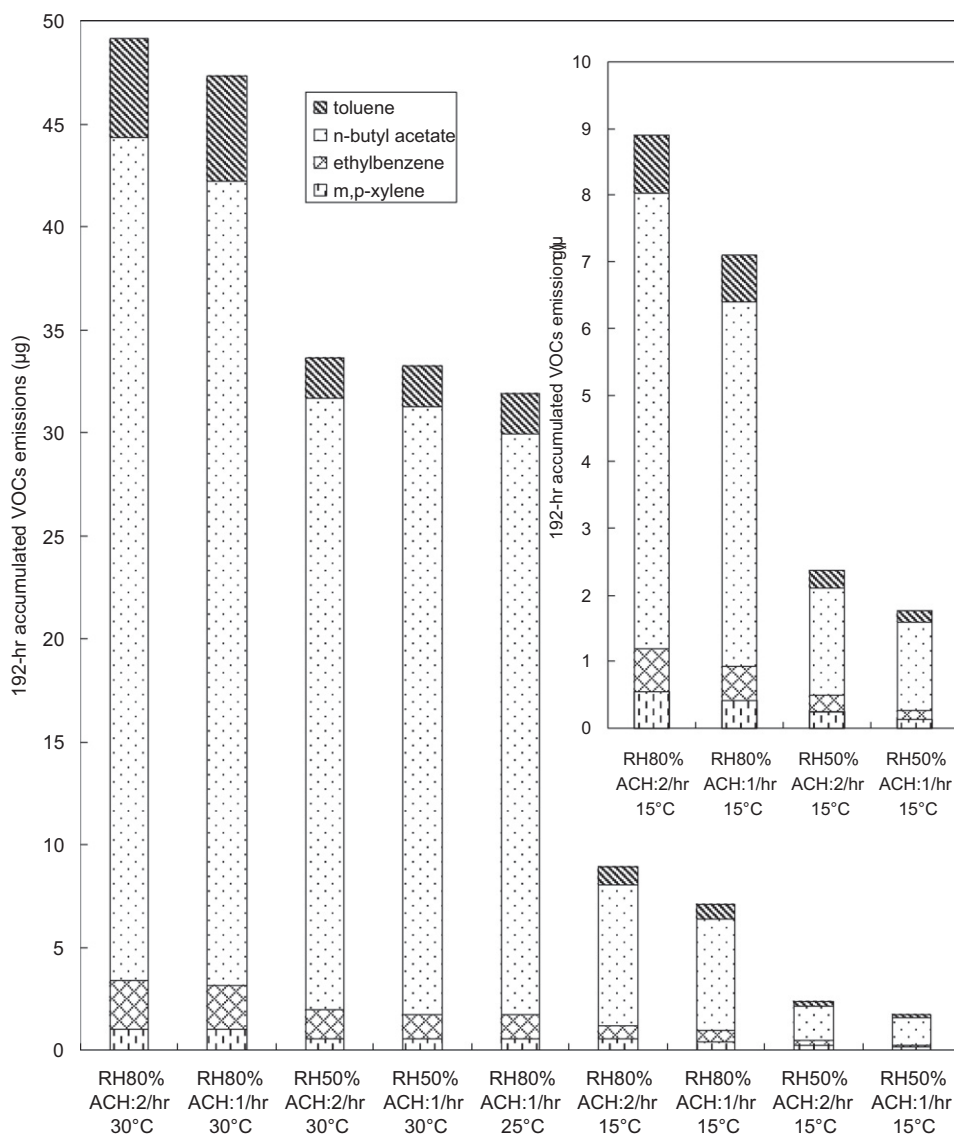


Fig. 6. VOC emissions accumulated for 192 h, $E_{ac}(192)$.

the air exchange rate increased from 1 to 2 h^{-1} . Meanwhile, toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene equilibrium concentrations decreased 13–40%, 23–37%, 12–36%, and 9–38%, respectively. The effect of air exchange rate on the reduction of VOC concentration at RH of 80% was larger than that at RH of 50%. The decrease of VOC concentrations in the gaseous phase would result in an increase of concentration gradient in the boundary layer between the surface of wooden flooring and the bulk phase of air stream. Thus, the molar flux of the VOCs through the boundary layer would also increase. According to our experimental data, when the air change rate increased from 1 to 2 h^{-1} , toluene, *n*-butyl acetate, ethylbenzene, and *m,p*-xylene initial and equilibrium SERs increased 6–74%, 15–53%, 14–76%, and 6–98%, respectively. The enhancement effect of air change rate on the VOC SERs under RH of 80% was greater than that at RH of 50%. It appears that an increase of air exchange rate may reduce the VOC concentration and the long- and short-term occupant exposures to VOCs. This finding is contrary to other observations at extremely controlled experimental conditions [7,11]. However, it is consistent with the findings from Dunn and Tichenor [15] and Wargocki et al. [17] that an increase of air

exchange rate can enhance the VOC SERs and decrease the steady-state VOC concentrations for externally controlled emissions. It is unknown whether any studies about air velocity impact on VOC emissions from wooden flooring have been performed. Again, generally, diffusion-controlled emissions are independent of the air exchange rate for most VOCs [18]. But the effect of air velocity depends on types of building materials and type of VOC emissions.

3.5. Accumulated VOC emission

As shown in Fig. 6, the VOC emissions accumulated for 192 h ranged from $49.16\text{ }\mu\text{g}$ (30°C , RH80%, and $\text{ACH} = 2\text{ h}^{-1}$) to $1.76\text{ }\mu\text{g}$ (15°C , RH50%, and $\text{ACH} = 1\text{ h}^{-1}$). The 192-h E_{ac} increased 5.5–18.9 times, as the temperature increased from 15 to 30°C . When the RH increased from 50% to 80%, the 192-h E_{ac} increased 1.46–4 times. The 192-h E_{ac} increased 1.2–35% when the air exchange rate increased from 1 to 2 h^{-1} . An increase of temperature, RH, and air exchange rate can enhance E_{ac} and thus reduce VOC residues in the wooden flooring. As a result, it appears that VOC residues in the wooden flooring can be significantly reduced

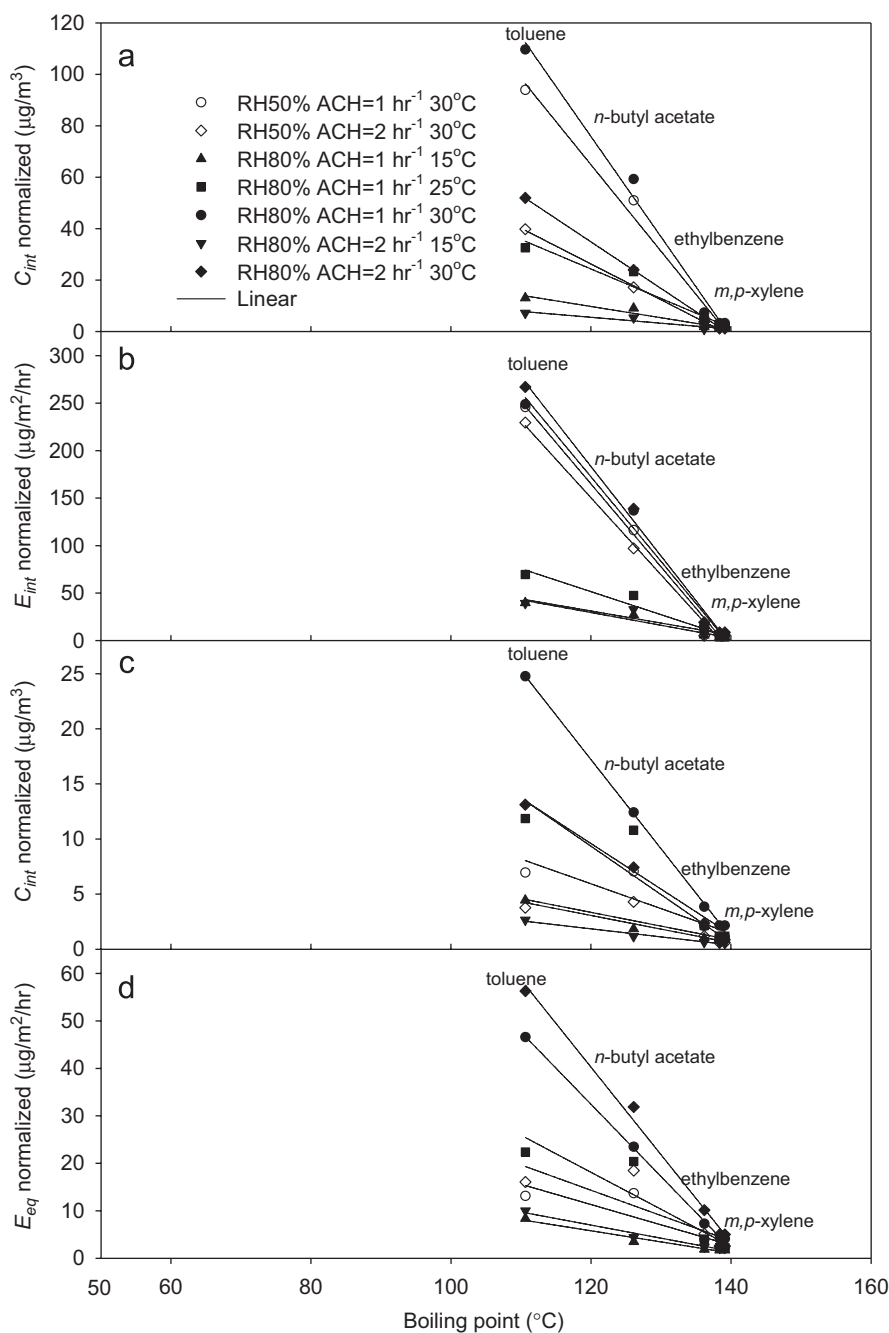


Fig. 7. Relations between boiling point of VOCs and (a) C_{int} normalized, (b) E_{int} normalized, (c) C_{eq} normalized, and (d) E_{eq} normalized (C_{int} normalized, E_{int} normalized, C_{eq} normalized, and E_{eq} normalized are C_{int} , E_{int} , C_{eq} , and E_{eq} divided by the content percentage of each VOC, respectively, boiling point data from CRC handbook of chemistry and physics, 81th ed., 2000–2001).

before a room is occupied by increasing temperature, RH and air exchange rate.

3.6. Boiling point, vapor pressure, and diffusivity

In order to eliminate the effect of variation of content percentages, we normalized the initial and equilibrium VOC SERs (E_{int} and E_{eq}) and concentrations (C_{int} and C_{eq}) by dividing C_{int} , E_{int} , C_{eq} , and E_{eq} with the content percentage of each VOCs. Fig. 7 shows the relations between the boiling points of VOCs and each of the normalized C_{int} , C_{eq} , E_{int} , and E_{eq} (C_{int} nol., C_{eq} nol., E_{int} nol., and E_{eq} nol.) are linear with negative slopes. The boiling point can affect VOC partition coefficient between the material and air. The higher the boiling point, the lower the VOC partition into the air.

The interceptions of boiling point axis are around 140 °C (ranged from 138.5 to 142.9 °C). There was no 2-ethylhexyl acrylate (boiling point = 214–218 °C) emission observed, even though the content percentage of 2-ethylhexyl acrylate was as high as 31.5%. Thus, VOCs whose boiling points are higher than 142.9 °C may not emit from the wooden flooring.

Another factor that affects partition coefficient is vapor pressure. The relations between the vapor pressures of VOCs and each of C_{int} nol., C_{eq} nol., E_{int} nol., and E_{eq} nol. are linear with positive slope as shown in Fig. 8 and 9. The interceptions of vapor pressure axis at 30, 25, and 15 °C are around 9 mmHg (ranged from 7.7 to 10.2 mmHg), 6.8 mmHg (ranged from 6.6 to 6.9 mmHg), and 2 mmHg (ranged from 1.2 to 3.2 mmHg), respectively. The vapor pressure of 2-ethylhexyl acrylate was 0.178 mmHg at 25 °C; there

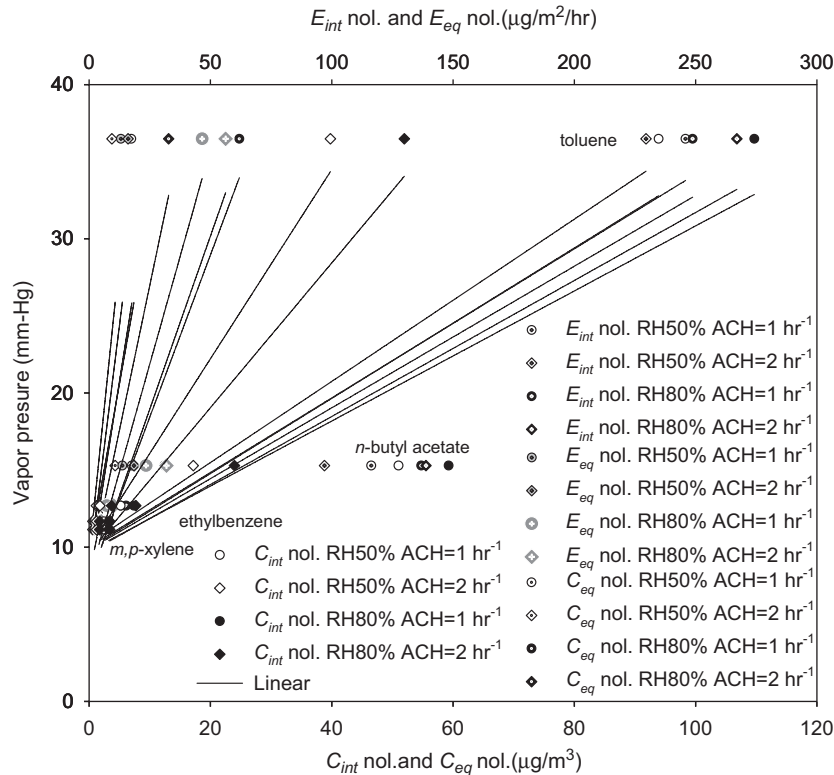


Fig. 8. Relations between vapor pressure of VOCs and each of C_{int} normalized, E_{int} normalized, C_{eq} normalized, and E_{eq} normalized at 30 °C

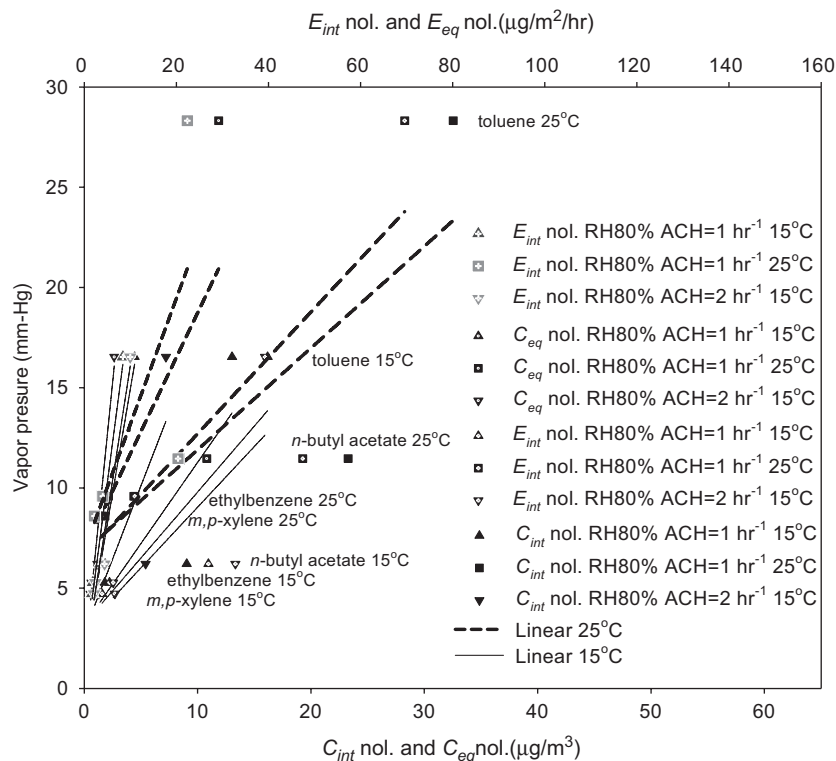


Fig. 9. Relations between vapor pressure of VOCs and each of C_{int} normalized, E_{int} normalized, C_{eq} normalized, and E_{eq} normalized at 15 and 25 °C.

was no 2-ethylhexyl acrylate emission observed. Therefore, VOCs whose vapor pressures are lower than 7.7, 6.6, and 1.2 mmHg at 30, 25, and 15 °C, respectively, may not be emitted from the wooden flooring.

The relations mentioned above are related to boiling points and vapor pressures of VOCs, revealing that under those experimental conditions, the VOC emissions may depend on the evaporation process. But at 15 °C and RH50%, these relations are

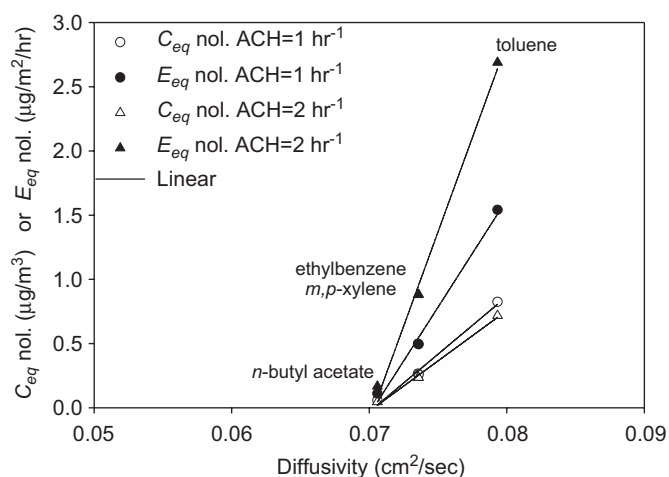


Fig. 10. Relations between diffusivities of VOCs and each of C_{eq} normalized and E_{eq} normalized under RH50% and 15 °C.

not applicable. As shown in Fig. 10, the relations between the normalized VOC equilibrium SERs and concentrations and the diffusivities of VOCs are linear with a positive slope at 15 °C, RH50%. Again, this is also consistent with Xu and Zhang [16] that diffusivity will positively impact VOC SERs and concentrations. The diffusivity-estimating method is given as Eq. (8). In Fig. 10, the interception of diffusivity axis is around 0.07 cm²/s. At 15 °C, the diffusivity of 2-ethylhexyl acrylate is 0.055 cm²/s, and no 2-ethylhexyl acrylate emission from wooden flooring was observed. Therefore, VOCs whose diffusivities are smaller than 0.07 cm²/s at 15 °C may not be emitted from the wooden flooring.

4. Conclusions

In this study, we demonstrated the effect of temperature, RH, and air exchange rate on the concentration–time profile of VOC SERs from wooden flooring through a 8-day chamber test. The wood tested in this study is not common solid wood, but composite wood made of combined wood fibers. Increase of temperature and RH had a positive effect on VOC SERs and concentrations. The enhancement effect of air exchange rate on the VOC SERs was significantly weaker than that of temperature and RH. However, the results are in strong disagreement with a number of previous studies about the influence of air exchange rate, and this needs further research to understand this discrepancy. In addition, type of VOC emissions, e.g. VOC properties, such as boiling point, vapor pressure, and diffusivities, also had similar strong effects on VOC SERs and correlated relations may be used to predict whether specific VOCs and what species of VOCs would be emitted. This study provides a rather detailed

characterization about how exactly these factors would affect VOC SERs and is in a good agreement with peer-reviewed literatures. The result might be also applied to evaluate the occupant exposure to VOCs.

Acknowledgment

The authors would like to thank National Science Council of Republic of China for funding this research project.

References

- [1] Wolkoff P, Wilkins C, Clausen P, Nielsen G. Organic compounds in office environments—sensory irritation, odor, measurements and the role or reactive chemistry. *Indoor Air* 2006;16:7–19.
- [2] Weschler C, Wells J, Poppendieck D, Hubbard H, Pearce T. Workgroup report: indoor chemistry and health. *Environmental Health Perspectives* 2006; 114(3):442–6.
- [3] Wolkoff P, Nielsen G. Organic compounds in indoor air—their relevance for perceived indoor air quality. *Atmospheric Environment* 2001;35:4407–17.
- [4] Wolkoff P. Volatile organic compounds—sources, measurements, emissions and the impact on indoor air quality. *Indoor Air* 1995;5(Suppl. 3):9–73.
- [5] World Health Organization. Indoor air quality: organic pollutants. In: EURO reports and studies, vol. 111. Copenhagen: Regional Office for Europe; 1989.
- [6] Fang L, Clausen G, Fanger O. Impact of temperature and humidity on perception of indoor air quality. *Indoor Air* 1998;8:80–90.
- [7] Wolkoff P. Impact of air velocity, temperature, humidity and air on long-term VOC emissions from building products. *Atmospheric Environment* 1998;32: 2659–68.
- [8] Van Netten C, Shirliffe C, Svec J. Temperature and humidity dependence of formaldehyde release from selected building materials. *Bulletin of Environmental Contamination and Toxicology* 1989;42:558–65.
- [9] Andersen I, Lundquist R, Molhave L. Indoor air pollution due to chipboard used as a construction material. *Atmospheric Environment* 1975;9:1121–7.
- [10] Sollinger S, Levens K, Wunsch G. Indoor pollution by organic emissions from textile floor coverings: climate test chamber studies under static conditions. *Atmospheric Environment* 1994;28:2369–78.
- [11] Knudsen H, Kjaer U, Nielsen P, Wolkoff P. Sensory and chemical characterization of VOC emissions from building products: impact of concentration and air velocity. *Atmospheric Environment* 1999;33:1217–30.
- [12] Colombo A, De Bortoli M, Pecchio E, Schauenburg H, Schlitt H, Visser H. Chamber testing of organic emission from building and furnishing materials. *The Science of the Total Environment* 1990;91:237–49.
- [13] ASTM Committee D22.05 on Indoor Air. ASTM D5116-06. Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products. West Conshohocken, PA, United States: ASTM International; 2006.
- [14] Guo H, Murray F, Wilkinson S. Evaluation of total volatile organic compound emissions from adhesives based on chamber tests. *Journal of the Air and Waste Management Association* 2000;50:199–206.
- [15] Dunn JE, Tichenor BA. Compensating for sink effects in emissions test chambers by mathematical modeling. *Atmospheric Environment* 1988;22: 885–94.
- [16] Xu Y, Zhang YP. An improved mass transfer based model for analyzing VOC emissions from building materials. *Atmospheric Environment* 2003;37: 2497–505.
- [17] Wargocki P, Bakó-Biró Z, Clausen G, Fanger PO. Air quality in a simulated office environment as a result of reducing pollution sources and increasing ventilation. *Energy and Buildings* 2002;34:775–83.
- [18] Wolkoff P, Salthammer T, Woolfenden A. Emission cells and comparison to small chambers for materials emissions testing. *Gefahrstoffe-Reinhardtung der Luft* 2005;65:93–8.