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Procedia Engineering 121 (2015) 59 – 66

Procedia Engineering

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9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

The Impact of Relative Humidity on the Emission Behaviour of Formaldehyde in Building Materials

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Abstract

Relative humidity (RH) is one of the main environmental factors affecting the emission behaviours of formaldehyde from building materials. Meanwhile, the initial emittable concentration ($C_{m,0}$) is proved to be the most sensitive key parameter to the emission behaviours. However, there is no report on the relationship between RH and $C_{m,0}$. In this paper, $C_{m,0}$ of formaldehyde from a type of medium density fiberboard in RH range of 20%-85% were tested by the ventilated C-history method. Experimental results show that $C_{m,0}$ increased by 10 times when RH rising from 20% to 85%. A linear relationship between ln($C_{m,0}$) and RH is obtained based on the experimental results. A correlation characterizing the association of emission rate and RH is also derived. With the correlations, the $C_{m,0}$ or emission rate different from test RH conditions can be conveniently obtained. This study should be useful for predicting the emission characteristics under varied RH conditions.

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Initial concentration; Formaldehyde; Relative humidity; Building material.

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Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015
doi:10.1016/j.proeng.2015.08.1019

Nomenclature

RH	relative humidity
K	partition coefficient
$C_{m,0}$	initial emittable concentration
D_m	diffusion coefficient
C_{equ}	equilibrium chamber concentration
C_a	the hourly formaldehyde concentration under ventilated condition
t	emission time
E	emission rate

1. Introduction

Poor indoor air quality caused by formaldehyde from building materials may decrease work efficiency and cause health-related problems [1] Short-term exposure to formaldehyde results in acute diseases, such as irritating responses of eyes, respiratory symptoms, headache, tiredness and asthma symptoms. Long-term exposure will even cause cancer [2]. In order to control the indoor formaldehyde pollution, it is urgently needed to understand and predict the source emission behaviours firstly.

The emission behaviours of formaldehyde from building materials can be characterized by the emission rate or three key parameters, i.e., the initial emittable concentration ($C_{m,0}$), the diffusion coefficient (D_m), and the partition coefficient (K). The emission rate or key parameters are not only dependent on the physical properties of the material-pollutant combinations but also affected by the environmental conditions, such as temperature and relative humidity[3-5]. Many experimental studies indicated that the emission rate and chamber concentration increased with increasing RH. Andersen et al. observed that the emission rate of formaldehyde from a kind of particleboard was doubled when RH increased from 30% to 70% [3]. Lin et al. (2009) reported that when RH increased from 50% to 80%, the emission rate and chamber concentration of toluene, n-butyl acetate, ethylbenzene, and m,p-xylene increased 3.5-5.4, 1.1-1.4, 1.8-3.8, and 1.5-3.5 times, respectively[4]. However, some other studies found that the impact of RH on the emission rate was not always positively correlated. For some scenarios it became ignorable or even negatively correlated for the tested material-pollutant combinations, and the reason for this phenomenon was unclear [6,7]. As far as the key parameters are concerned, they are all targeted at the impact of RH on D_m and K. The negligible effect of RH on D_m is gained by many studies, but things become a little complicated for the impact RH on K.

However, there is no report about the influence of RH on $C_{m,0}$, which is proved to be the most sensitive key parameter to the emission behaviours [8]. In addition, there is no correlation between the emission rate and RH from theoretical studies, which prevents determining the emission rate at RH different from the test conditions.

For the above reasons, this article aims at studying the impact of RH on $C_{m,0}$ for formaldehyde emissions from building materials in the RH range of 20%-85% and deriving a correlation between the emission rate and RH by virtue of theoretical approach.

2. Methods for determine 3 key parameters

2.1. The principle of the ventilated C-history method

A rapid and accurate method, the ventilated chamber C-history method [9], is applied to determine the three key emission parameters ($C_{m,0}$, D_m, K). This method comprises two physical processes. The first process is emission under airtight condition. The tested building material is placed in an airtight chamber until equilibrium. The second process is emission under ventilated condition. Figure 1 shows the concentration change tendency of formaldehyde in the chamber during these two emission processes.

For the first process, the equilibrium chamber concentration can be expressed as:

$$C_{\mathrm{equ}} = \frac{C_{\mathrm{m,0}}}{K + R} \tag{1}$$

where, R is defined as the ratio of chamber volume (V_{c}) to material volume (V_{m}).

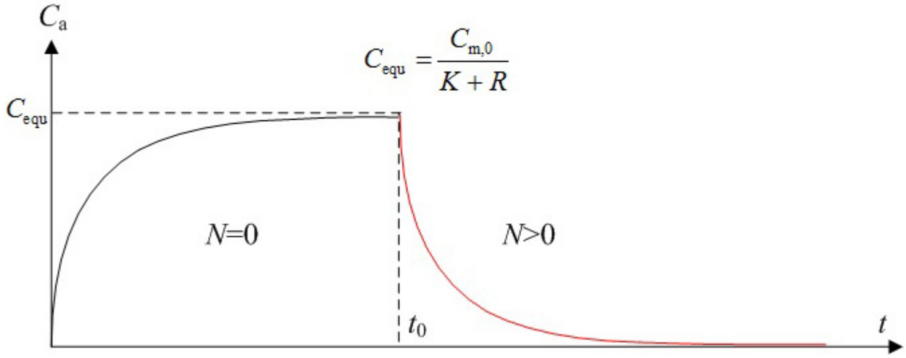

Fig. 1. Changes of the chamber formaldehyde concentration during the airtight and ventilated processes.

For the second process, a linear relationship between $\ln(C_{\mathrm{a}}(t)/C_{\mathrm{equ}})$ and t can be derived:

$$\ln \frac{C_{\mathrm{a}}(t)}{C_{\mathrm{equ}}} = \mathrm{SL} \cdot t + \mathrm{INT} \tag{2}$$

where, C_{a} is the hourly formaldehyde concentration under ventilated condition, μg/m^3; t is the emission time under ventilated condition, s; SL and INT are functions of D_{m} and K.

Once C_{equ} and C_{a} are measured, and then substituted into equation (2), SL and INT can be determined from linear curve fitting. D_{m} and K, which are functions of SL and INT, can be conveniently obtained by solving the two equations. Then, by combining the determined K with equation (1), $C_{\mathrm{m,0}}$ can be calculated.

2.2. Experimental condition

In order to investigate the relationship between $C_{\mathrm{m,0}}$ and RH, the experiments are carried out under 5 different RHs, i.e., 20±5%, 40±5%, 55±5%, 65±5% and 85±5%. The air temperature in the chamber is controlled at 25.0±0.5°C. The geometrical dimensions of the tested building material and experimental conditions are listed in Table 1.

Table 1. An example of a table Experimental conditions of the tested building material.

RH (%)	Temperature(°C)	Dimensions(cm×cm×cm)	Number of pieces
20±5			
40±5			
55±5	25±0.5	10.0×10.0×0.3	4
65±5			
85±5			

3. Results and discussions

3.1. Key parameters determined by the ventilated C-history method

The measured key parameters of formaldehyde and the corresponding R^2 at 5 different RHs are summarized in table 2.

Table 2. Determined key emission parameters based on ventilated chamber C-history method at 5 different RHs.

RH (%)	$C_{m,0}$ (μg/m^3)	D_m (m^2/s)	K	R^2
20±5	2.07×10^{6}	8.57×10^{-11}	1.34×10^{3}	0.90
40±5	4.63×10^{6}	1.49×10^{-10}	2.06×10^{3}	0.99
55±5	5.98×10^{6}	1.10×10^{-10}	3.04×10^{3}	0.98
65±5	1.43×10^{7}	1.31×10^{-10}	3.61×10^{3}	0.98
85±5	2.39×10^{7}	1.14×10^{-10}	4.33×10^{3}	0.94

The determined parameters should be validated to prove its reliability. We calculate the chamber formaldehyde concentration using an analytical model based on the parameters given in Table 2, and then compare it with the experimental data. Good agreements demonstrates the effectiveness of the measured parameters. Because of space constraints, only the comparison at 20%RH is shown in Figure 2.

3.2. The correlation between Cm,0 and RH

According to the determined $C_{m,0}$ listed in Table 2, $C_{m,0}$ of formaldehyde increases greatly with the increase of RH. When RH increases to 85%, $C_{m,0}$ is about 11 times of that at 20%RH. After taking logarithm of $C_{m,0}$ at different RHs, we found that ln$C_{m,0}$ is in a good linear relationship with RH formaldehyde (Figure 3).

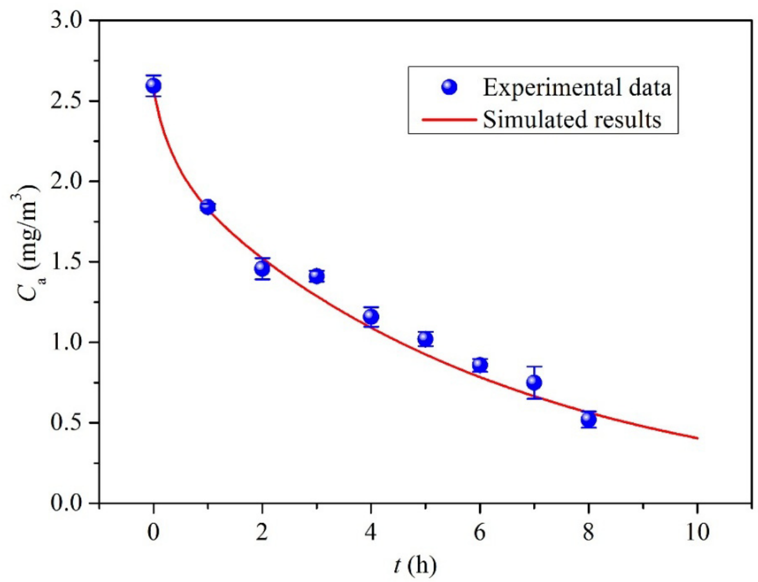

Fig. 2. Comparison of chamber formaldehyde concentration between the simulated results and experimental data at 20%RH.

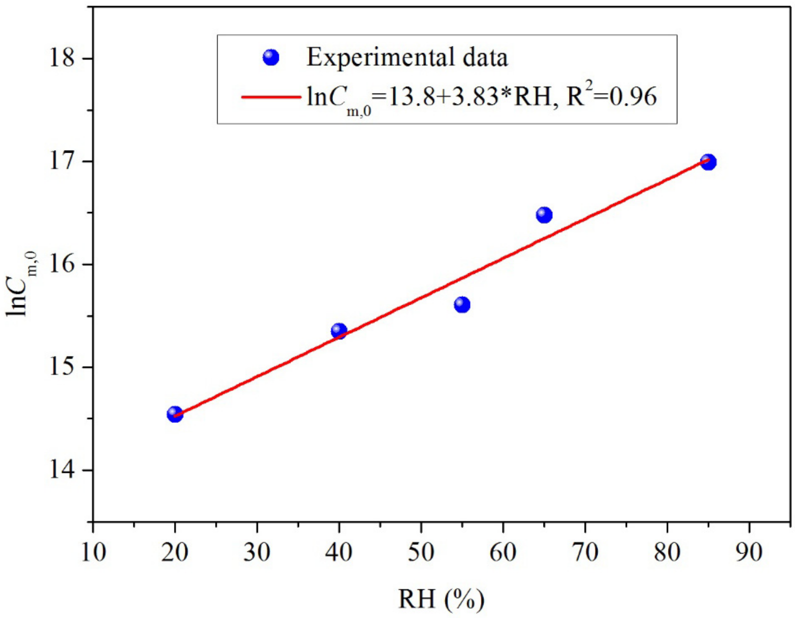

Fig. 3. The relationship between logarithm of Cm,0 and RH.

Based on the above analysis, the correlation between $C_{\mathrm{m},0}$ and RH for formaldehyde in the tested MDF can be expressed as:

$$\ln C_{\mathrm{m},0} = C_1 \cdot \mathrm{RH} + C_2 \tag{3}$$

where, C_1, C_2 are constants, which are only related with the physical properties of the material-pollutant combinations. Once two or more sets of experimental data are available to determine the parameters C_1 and C_2 in equation (3), this correlation can then be applied to evaluate $C_{\mathrm{m},0}$ at other RHs, which is very useful.

3.3. The theoretical correlation between emission rate and RH

For the impact of RH on the emission rate, traditional studies are all based on experimental investigations. In this section, we devote to derive a theoretical correlation based upon the aforementioned results. When the emissions of formaldehyde from building materials reach steady state, the emission rate can be expressed as:

$$E(t) = 2.1\frac{D_{\mathrm{m}} C_{\mathrm{m},0}}{L}\exp(-2.36\frac{D_{\mathrm{m}} t}{L^2}) \tag{4}$$

where, E is the emission rate factor, μg/(m^2·h).

According to the results in the present and traditional studies, RH has no obvious impact on D_{m}. Therefore, the term $2.1D_{\mathrm{m}}/\delta$ can be regarded as a constant irrelevant with RH and equation (4) can be written as:

$$E(t) = AC_{\mathrm{m},0}\exp(-2.36 Fo_{\mathrm{m}}) \tag{5}$$

where, A=2.1D_{m}/δ.

Taking logarithm on both sides of equation (4), it yields:

$$\ln E(t) = \ln C_{m,0} + \ln A - 2.36 Fo_m \tag{6}$$

Combining this equation with equation (3), we get:

$$\ln E(t) = E_1 \cdot \mathrm{RH} + (E_2 - 2.36 Fo_m) \tag{7}$$

where, $E_1=C_1$, $E_2=\ln A+C_2$.

Considering that Fo_m is approximately 0.2 when the emissions reach steady state and is taken as 2.0 when the emissions are completed, the term $2.36Fo_m$ is relatively small compared with other terms. Therefore, equation (7) can be further simplified as:

$$\ln E = E_1 \cdot \mathrm{RH} + E_2 \tag{8}$$

where, the parameters E_1 and E_2 in this equation are independent on RH.

The above equation indicates that the logarithm of the emission rate is linearly associated with RH. Once the steady state emission rate at two or more different RHs are measured, E_1 and E_2 can be determined by solving equations or linear curve fitting, then the emission rate at a certain RH different from the test conditions can be calculated by equation (8).

3.4. Validation

The experimental data of formaldehyde emissions from MDF is applied to validate the derived correlation. Theoretically, the emission rate is a function of the three key parameters ($C_{m,0}$, D_m, K). Therefore, we can calculate the steady state emission rate by applying an analytical model. Figure 4 shows the calculated results (t=40h) at 5 different RHs (20%, 40%, 55%, 65%, and 85%). It reveals that ln$E$ changes linearly with RH, with R^2 being 0.95, implying the derived correlation for emission rate is effective and reliable.

The experimental data in literature are also taken to further validate the derived correlation. Sidheswaran et al. measured the emission rate of formaldehyde from different filters at different RHs under high wind speed and low wind speed [10]. By using the correlation (equation (7)) to treat the experimental data, the results are shown in Figure 5, which reveals that, when other environmental conditions are fixed, ln$E$ confirms a good linear relationship with RH.

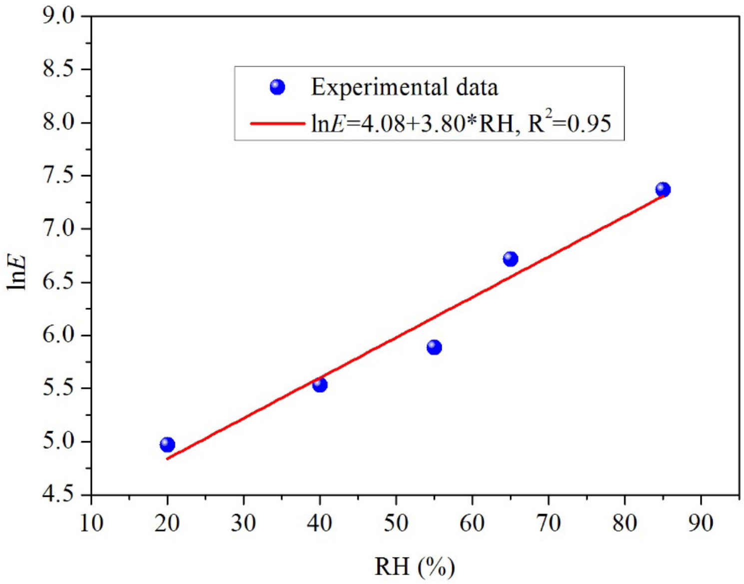

Fig. 4. Validation of the derived correlation for emission rate with experimental data.

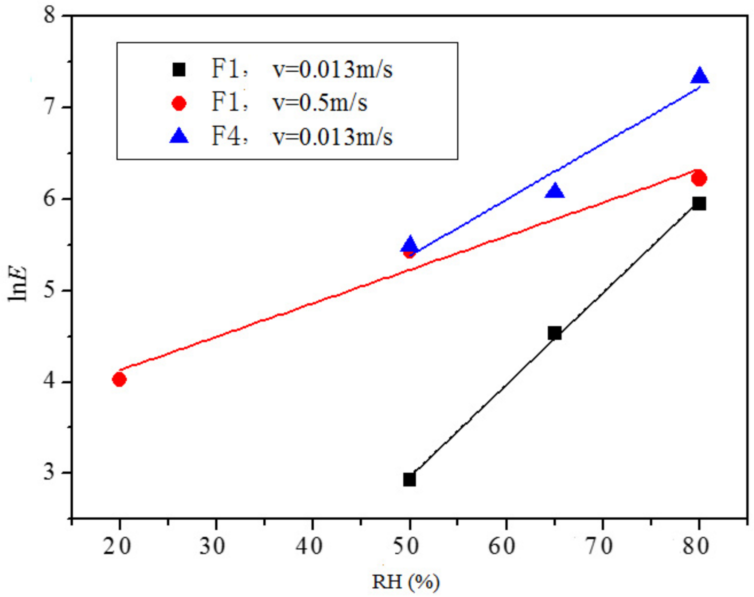

Fig. 5. Validation of the derived correlation for emission rate with experimental data from literature.

4. Conclusion

This paper investigates the impact of relative humidity on the initial emittable concentration ($C_{m,0}$) of formaldehyde emission from a kind of medium density fibreboard. Experimental results indicate that $C_{m,0}$ changes significantly with RH in the range of 20%-85%. A linear association between logarithm of $C_{m,0}$ and RH is obtained via regression of the tested results. Furthermore, a novel correlation to describe the relationship between the emission rate and RH is derived theoretically, which is more advantageous than the traditional studies focused on experimental exploration. It will be effective and reliable for evaluating the formaldehyde emission from building materials under varied RH conditions.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 51106011, No. 51476013, No. 51136002), the 12th 5 Year Key Project, Ministry of Science and Technology of China (No. 2012BAJ02B01).

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