Mathematical Model for the Formaldehyde Emission from Wood Composites

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Abstract

Because of the possibility of harmful formaldehyde emissions from industrial-produced wood composites, the influence of temperature, relative humidity, and frequency of ventilation on formaldehyde emission from particleboard, plywood and fiberboard respectively, were investigated in this article. An improved generally applicable model for calculating the formaldehyde emission from wood composites was established by using the iteration method, a double exponential attenuation model, and mass transfer theory. The model parameters for the emission of formaldehyde from wood composites are also discussed in this article. It is concluded that a high-temperature or high-humidity environment will promote the emission of formaldehyde from wood composites. The process of emission of formaldehyde from wood composites can be divided into quick-release, slow-release, and release saturation phases. The formaldehyde concentration can be predicted from the formaldehyde mathematical model, and the maximum difference between observed and predicted formaldehyde concentrations is less than 15 percent under different general environmental conditions.

Historically, wood composites are one of the most common materials used for indoor decoration. However, raw material, such as urea-formaldehyde (UF) glue, which contains high levels of formaldehyde, is used in the production process of wood composites. Formaldehyde is one of the main indoor airborne pollutants and is considered a dubious carcinogen by the World Health Organization of the United Nations (WHO) and the US Environmental Protection Agency. Because the use of formaldehyde is a health concern, it has become a topic of interest for many researchers. Most people spend more than 80 percent of their time indoors (Klepeis et al. 2014). Therefore, constant formaldehyde emissions have become an increasingly more serious problem for both humans and the environment. Excessive concentrations of formaldehyde in indoor settings from wood composites have become an important cause of sick building syndrome (WHO 1983). The US Congress has proposed a bill titled ''Formaldehyde Standards for Composite Wood Products Act'' to regulate the emissions of formaldehyde from composite wood products (Frost 2013). In the United States, formaldehyde is regulated by a number of agencies that aim at the larger manufacturers of particleboard, medium-density fiberboard, and interior plywood. This standard restricts formaldehyde emissions to very low limits.

Researchers have studied the formaldehyde emission process for wood composites (Guo et al. 2004, Qin et al. 2009, Salem et al. 2011, Shan et al. 2013, Chi et al. 2014).

Salem et al. (2011) estimated that the main environmental factors that affect formaldehyde emission from wood composites include temperature, humidity and ventilation rate. Based on experimental data, an exponent attenuation model for formaldehyde emissions has been put forward (Shan et al. 2013). A double exponential decay model of the total volatile organic compounds emitted from carpet has been established (Guo et al. 2004). Likewise, a more complete mathematical model for the formaldehyde emission from wood composites based on the theory of mass transfer has also been established (Little 1994, Yang 1999).

However, an empirical model has not been established based on the experimental data under certain environmental conditions. Where varying environmental conditions are not considered, the resulting model would not reflect the distribution mechanism and could not be applied when environmental conditions change. Based on the essence of formaldehyde diffusion from wood composites, it seems that a mass transfer model would provide more accurate

predictions and versatility for estimating formaldehyde concentrations. However, such a model also includes prediction error due to the simplified process of model building, such as seen in the model of Little (1994), which ignores spread mass transfer resistance, leading to larger deviations when predicting short-term emission of formaldehyde. Yang (1999) and Huang and Haghighat (2002) presented models that also considered the mass transfer resistance, but the former results in a larger prediction error because it ignores the influence of the indoor pollutants' initial concentration when the formaldehyde concentration of wood composites is too low or divergent at the beginning of the release experiment. The latter model uses a numerical solution, which is a complex process with low similar generalization; a semianalytical model has been put forward by Xu and Zhang (2003), but it is too complicated in predicting actual formaldehyde emissions.

This article uses a double exponential decay model and the iterative method to determine which physical parameters are relevant, in combination with the theory of mass transfer, to build a model for formaldehyde emission from wood composites. This approach effectively avoids errors caused by critical assumptions put forth in the mass transfer theory. This article aims to develop a simple mathematical model for formaldehyde emission from wood composites that will describe the formaldehyde emission mechanism and the control countermeasures that are necessary.

Materials and Methods

Materials

Cane fiber (Bagasse) was uesd to manufacture particleboard examined in the study. The particleboard was manufactured by bagasse with UF resin (F:U = 1.2:1) with a 60 percent solid content. The density and resin content of the particleboard was 520 kg/m^3 and 6 percent, respectively. Black pine (*Pinus thunbergii* Parl) was the wood species used to manufacture the plywood examined in the study. Five-layer plywood panels that were 12 mm thick were manufactured using UF resin (F:U = 1.7:1) with 47 percent solid content, and the density of each layer of 2.4-mm-thick veneers was approximately 620 kg/m^3. The density and resin content of the plywood was 600 kg/m^3 and 4 percent, respectively. Fir fiber and UF resin (F:U = 1.2:1) with 60 percent solid content were used as raw materials for the fiberboard production used in the study. The density and resin content of fiberboard was 720 kg/m^3 and 10 percent, respectively. No wax emulsion or any other additives were used for panel manufacturing. All fresh boards, cut directly at the hot-press outlet, were used as sample material. Three kinds of wood composites were each cut into three specimens with a three-dimensional size of 100 by 50 by 12 mm and sealed using aluminum tape. They were wrapped in aluminum foil and stored in evacuated polypropylene bags to prevent formaldehyde release. The panels were conditioned at 20°C ± 2°C with 65% ± 5% relative humidity for approximately 3 weeks and then cut into test specimens according to EN 326 standard (European Committee for Standardization [CEN] 1993).

Methods

All testing was conducted in accordance with EN 717-1 (CEN 2004). The main environmental factors, such as temperature, humidity, and ventilation rate, which affect formaldehyde release from samples, were investigated in the environmental test chamber (HW-571, studio volume = 1 m^3; Jinan Hong Wei Technology Co., Ltd.). The concentration of formaldehyde emissions was measured by examining the concentration of formaldehyde absorbed in water using a UV-Vis spectrophotometer based on the Hantzsch reaction. In the Hantzsch reaction, formaldehyde reacts with ammonium acetate and acetylacetone, yielding diacetyldihydrolutidine, which was quantified by evaluating the characteristic UV peak centered at 412 nm. Each chamber experiment mentioned above was completed over a 10-day period. Results indicate that the formaldehyde concentration in the environmental chamber will reach equilibrium concentration after approximately 10 hours, with a less than 3 percent difference between formaldehyde concentration after this point in time. Formaldehyde concentrations measured 10 hours after the start of experiment are listed for the purpose of developing a representative mathematical model for formaldehyde emission from wood composites.

Results and Discussion

Establishment of the formaldehyde emission model for wood composites

Formaldehyde emission from wood composites includes mainly three mass transport processes: (1) the internal diffusion process: the diffusion of formaldehyde from inside the wood composites to the surface; (2) the thermodynamic equilibrium process: absorption and stripping of formaldehyde between the air and the source interface; and (3) the convection transfer process: the diffusion of formaldehyde from the source boundary layer to the air. Formaldehyde transmission depends mainly on the first two processes, and the specific process is shown in Figure 1.

Assuming that the formaldehyde diffusion process from inside wood composites follows Fick's second theorem, the process can be introduced into a pure diffusion mass transport model (Spengler and Samet 2001):

$$E_s(t) = (0.632/\lambda)M_0(D/t)^{1/2} \qquad (1)$$

where $E_s(t)$ (mg/h·m^2) is the internal transfer rate of formaldehyde within wood composites, λ (m) is the thickness of the wood composites, M_0 (mg/m^2) is the initial release concentration of formaldehyde from wood compos-
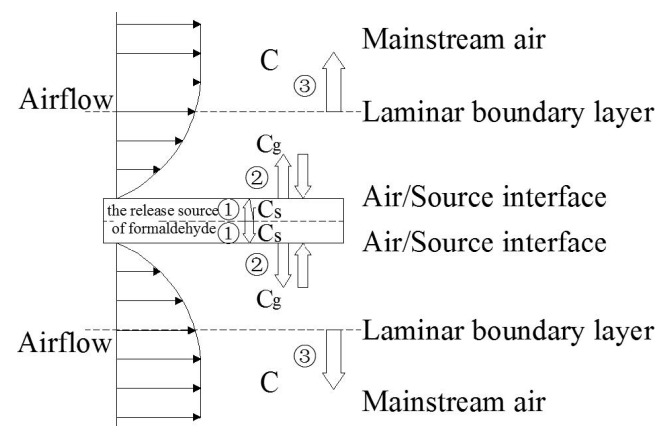

Figure 1.—Diagram of formaldehyde emission process from wood composites.

ites, D (m^2/h) is the formaldehyde internal diffusion coefficient for wood composites, and t (h) is time.

The process of thermodynamic equilibrium between the formaldehyde concentrations in the surface layer of the wood composites and the ambient can be expressed as follows (Little 1994):

$$C_s(t) = KC_g(t) \qquad (2)$$

where $C_s(t)$ is the formaldehyde concentration (mg/m^3) present between the air and the source interface, $C_g(t)$ (mg/m^3) is the formaldehyde concentration in the air, and K is the formaldehyde distribution coefficient between wood composites and air.

Given that formaldehyde mixes uniformly in the mainstream air, the convection transport process can be expressed as follows (Huang and Haghighat 2002):

$$E_g(t) = h_g \big[C_g(t) - C(t) \big] \qquad (3)$$

where $E_g(t)$ (mg/h·m^2) is the transmission rate of the formaldehyde into the air phase, h_g (m/h) is the mass transfer coefficient of formaldehyde in the air phase, and $C(t)$ (mg/m^3) is the formaldehyde concentration in indoor air.

Taking the whole process of formaldehyde emission from wood composites into consideration, Equations 1 to 3 can be translated into a new expression:

$$E_g(t) = h_g \left[\frac{0.632 M_0 (Dt)^{1/2}}{f\lambda^2 K} - C(t) \right] \qquad (4)$$

where f is the dimensionless thickness correction factor of wood composites.

The dC emission of formaldehyde from wood composites, in time dt, can be represented as

$$dC = \frac{A E_g(t) dt}{V} \qquad (5)$$

where A (m^2) is the area of the wood composites and V (m^3) is the volume of interior space.

By putting Equation 4 into Equation 5, the analytical expression of the formaldehyde concentration in wood composites, $C(t)$, can be derived using the Laplace transformation:

$$C(t) = \frac{0.632\lambda ANM_0}{K\lambda A + V} + 2NM_0 h_g \sum_{n=1}^{\infty} \frac{\sin q_n}{q_n \alpha_n} \exp^{-\frac{D}{f\lambda^2 K} q_n^2 t} \quad (6)$$

where $\alpha_n = (K\lambda N - [KDq_n/\lambda h_g + 1]\cos q_n - [2KD/\lambda h_g + 1]q_n \sin q_n$; $N = A/V$, α_n m^2/m^3, denotes loading rate, and q_n is a positive root of the transcendental equation

$$\frac{\tan q_n}{q_n} = \frac{\lambda h_g}{KDq_n^2 - Kh_g\lambda^2 N} \quad (n = 1, 2, \dots)$$

Parameter determination for the formaldehyde emission model

The main parameters in the formaldehyde emission model are from Equation 6, and most of these may be obtained from experimental measurement. Thus, N, V, and A are all known, while λ was obtained by direct measurement of the composites slab thickness. This leaves the distribution

coefficient between wood composites and air K, the mass transfer coefficient D of formaldehyde inside the wood composites, the mass transfer coefficient h_g of formaldehyde in the air phase, the initial release concentration M_0 of formaldehyde from wood composites, and the thickness correction factor f of the wood composites. These five parameters are necessary for the formaldehyde emission model and obtained in an iterative fashion (described below) using the chamber concentration data (Saez and Rittmann 1992, Little 1994, Xu and Zhang 2003, Guo et al. 2004).

Assuming that the initial formaldehyde concentration in the wood composites and in the indoor space are C_{0s} and C_{0g}, respectively, the formaldehyde concentration would reach equilibrium after a period of time, and their formaldehyde concentrations are C_{1s} and C_{1g}, respectively. For Equation 2, the following equation can be obtained:

$$C_{1s} = KC_{1g} \qquad (7)$$

According to the law of conservation of mass, there is

$$C_{1s}V_s + C_{1g}(V - V_s) = C_{0s}V_s + C_{0g}(V - V_s) \qquad (8)$$

where V_s is the volume of the wood composites (m^3). Hence,

$$(C_{0g} - C_{1g})n = KC_{1g} - C_{0s} \qquad (9)$$

where $n = (V - V_s)/V_s$ is a constant term.

The distribution coefficient K between wood composites and air, along with the initial formaldehyde concentration C_{0s}, can be obtained by linear fitting using Equation 9 and measuring the series of initial formaldehyde concentrations C_{0g} and C_{1g}.

Considering that the formaldehyde concentration in the wood composites is considerably great than the indoor concentration, the excessive residual formaldehyde concentration can be defined as $C' = C_s - KC_g\infty$ and the dimensionless residual concentration as $C^* = C'/C_0 s - KC_g\infty$. The Biot number for mass transfer is $Bi = \lambda h_g/DK$. Both the mass transfer Fourier number $Fo = Dt/\lambda^2$ and equation $X = x/\lambda$ are dimensionless, where x is the thickness of the side of the wood composites between the air and the source interface (m).

Then, in light of the study by Little (1994), the boundary and initial conditions of the dimensionless governing equations for wood composites formaldehyde diffusion are as follows:

$$\frac{\partial C^*}{\partial Fo} = \frac{\partial^2 C^*}{\partial X^2} \qquad 0 < X < 1, \quad Fo > 0 \qquad (10)$$

$$C^* = 1 \qquad 0 \leq X \leq 1, \quad Fo = 0 \qquad (11)$$

$$\frac{\partial C^*}{\partial X} = 0 \qquad X = 0, \quad Fo > 0 \qquad (12)$$

$$\frac{\partial C^*}{\partial X} = -BiC^* \qquad X = 1, \quad Fo > 0 \qquad (13)$$

In light of Xu and Zhang (2003), Equations 10 to 13 can be simplified to

$$C^* = 2\sum_{n=1}^{\infty} e^{-\beta_n^2 Fo} \frac{\sin \beta_n \cos \beta_n X}{\beta_n + \sin \beta_n \cos u_n} \qquad (14)$$

where β_n is the positive root of the transcendental equation, $tg(\beta_n) = Bi/\beta_n$, $n = 1, 2, 3, \ldots$.

When $Fo > 0.2$, the difference in formaldehyde concentration in Equation 14 between the first item calculated by series and at $X = 0$ calculated by the complete series is less than 1 percent (Xu and Zhang 2003). At this point, the ratio of excessive concentration between any point and the most lateral point in the wood composites has no relationship with time. Therefore,

$$\frac{C'_s(X)}{C'_{0s}} = \frac{\cos(\beta_n X)}{\cos(\beta_n)} \quad (15)$$

The formula $C'_s(X)/C'_{0s} = 1$ is true when X is held constant value, and at this point the dimensionless thickness correction factor $f = X$. The corresponding value f can be calculated by C_{0s}.

The infinite series summation item in Equation 6 would tend toward 0 as time (t) lapses. Thus, the equilibrium concentration of formaldehyde can be simplified to

$$C_{equ} = \frac{0.632 \lambda A N M_0}{K \lambda A + V} \quad (16)$$

Transforming the formaldehyde concentration in Equation 6 and equilibrium concentration in Equation 16 into a new equation yields the following:

$$\frac{C_{equ} - C(t)}{C_{equ}} = -2 \frac{(K\lambda A + V)h_g}{0.632\lambda A} \sum_{n=1}^{\infty} \frac{\sin q_n}{q_n \alpha_n} \exp^{-\frac{D}{f\lambda^2 K} q_n^2 t} \quad (17)$$

While the amount of time (t) that is needed is great, the $n = 1$ is the main item, and the other items could be negligible due to the quick attenuation for the right index summation item from Equation 17, meaning that Equation 17 can be processed linearly as follows:

$$\ln\left(\frac{C_{equ} - C(t)}{C_{equ}}\right) = -\frac{Dq_1^2}{f\lambda^2 K}t + \ln\left(-\frac{2(K\lambda A + V)h_g \sin q_1}{0.632\lambda A q_1 \alpha_1}\right) \quad (18)$$

where q_1 is the first root of the transcendental equation and α_1 is the first item of α_n.

Thus, we can obtain the formaldehyde internal diffusion coefficient D for the inside of wood composites by the slope of the line representing the formaldehyde emission process under multiple distributing conditions present in Equation 18.

The mass transfer coefficient h_g of formaldehyde in the air phase is determined using two mass transfer characteristic-related formulas as follows (Yao et al. 2011):

$$Sh = 0.664 \text{Re}^{1/2} Sc^{1/3} \quad (19)$$

$$h_g = Sh\left(\frac{D}{\lambda}\right) \quad (20)$$

The concentration of formaldehyde released from the wood composites can be obtained using the time integration of concentration in Equation 5. Predicted concentrations can be obtained using a linear model of experimental results under different experimental conditions. Then, according to the law of conservation of mass, the actual amount of formaldehyde emission emitted from wood composites M_0

under different environmental conditions, would be determined by integrating time ($0 \rightarrow \infty$) under the corresponding condition:

$$M_0 = \frac{\int_0^{\infty} C(t)Qdt}{A} \quad (21)$$

In this equation, Q is the ventilation volume of the environmental chamber (m^3/h).

Hence, $E(t)$ in Equation 5 can be determined using the double exponential decay model (Guo et al. 2004):

$$E(t) = E_{01}e^{-k_{01}t} + E_{02}e^{-k_{02}t} \quad (22)$$

where E_{01} and E_{02} are the fast and slow initial transmission rates (mg/[h·m^2]), respectively, and k_{01} and k_{02} denote the fast and slow attenuation constants (h^{-1}), respectively.

The data, including measured formaldehyde concentrations in Equation 22, are applied to the calculation by iteration, under different experimental conditions, after which the double exponential decay model parameters can be deduced in different experimental conditions. The results are shown in Figures 2 through 4.

Figures 2 through 4 show that, with an increase in environmental temperature, humidity, and ventilation rate, in a double exponential decay model, the parameters for fast and slow initial transmission rates, E_{01} and E_{02}, and attenuation constants, k_{01} and k_{02}, would increase when the other experimental conditions remain unchanged. It also shows that high temperature, high humidity, and ventilation rate are advantageous to enhance the diffusion ability of formaldehyde from wood composites, while the influence of the ventilation rate is relatively weak.

Model parameters for the emission of formaldehyde from wood composites

Parameters for the model of formaldehyde emission from wood composites, according to the experimental data from Figures 5 through 7, are shown in Tables 1 through 3. From Tables 1 through 3, it can be seen that a high-temperature and high-humidity environment would promote emission of formaldehyde from wood composites. With an increased ventilation rate, the formaldehyde concentration between the air and source of interface would increase, thus promoting the diffusion of formaldehyde to the mainstream air and reducing the formaldehyde concentration on the surface of the wood composites. In addition, environmental factors exert little effect on the distribution coefficient K and the mass transfer coefficient h in the air phase.

Experimental analysis of formaldehyde release from wood composites

The relation curve between time and release of formaldehyde concentration from wood composites under different environmental conditions is shown in Figures 5 through 7. The overview of experimental design is shown in Table 4.

Figures 5 through 7 show that environmental factors, such as temperature, humidity, and ventilation rate, influence formaldehyde emissions from wood composites, which can be divided into the quick-release, slow-release, and release saturation phases over time. With increasing temperatures and humidity or with decreases in the
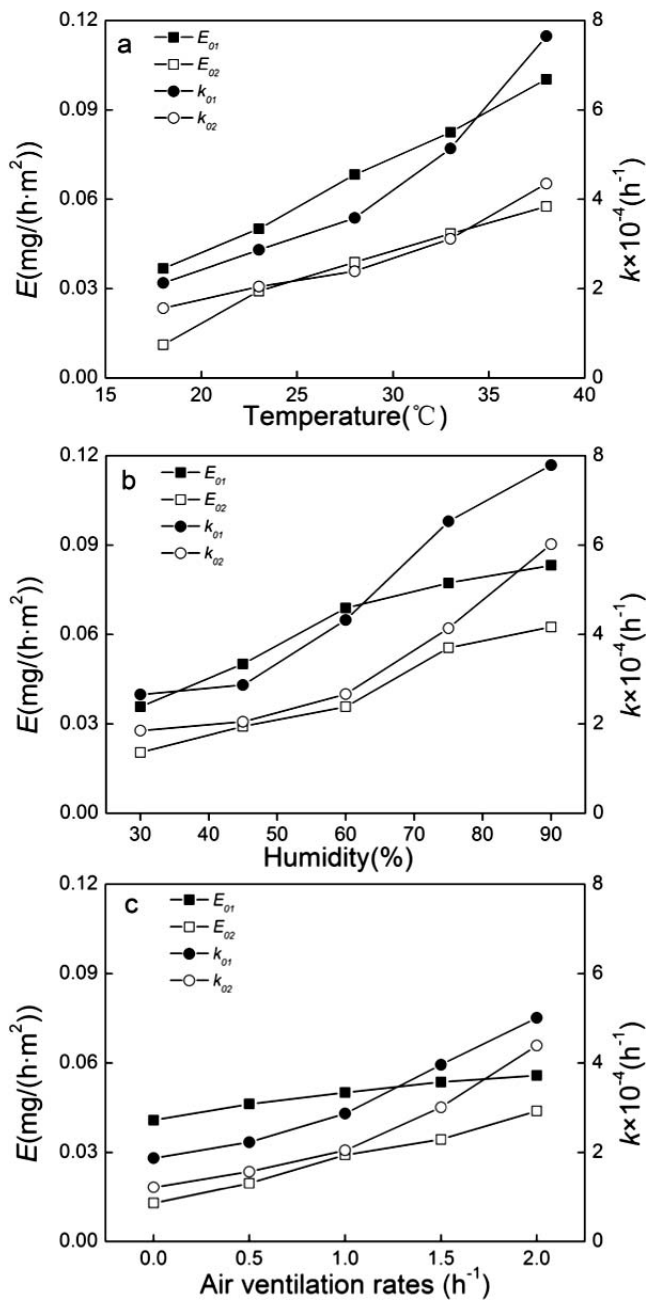
Figure 2.—Effect of environmental conditions on parameters of particleboard's double exponential model. The specific experimental conditions of parts a through c are shown in Table 4.
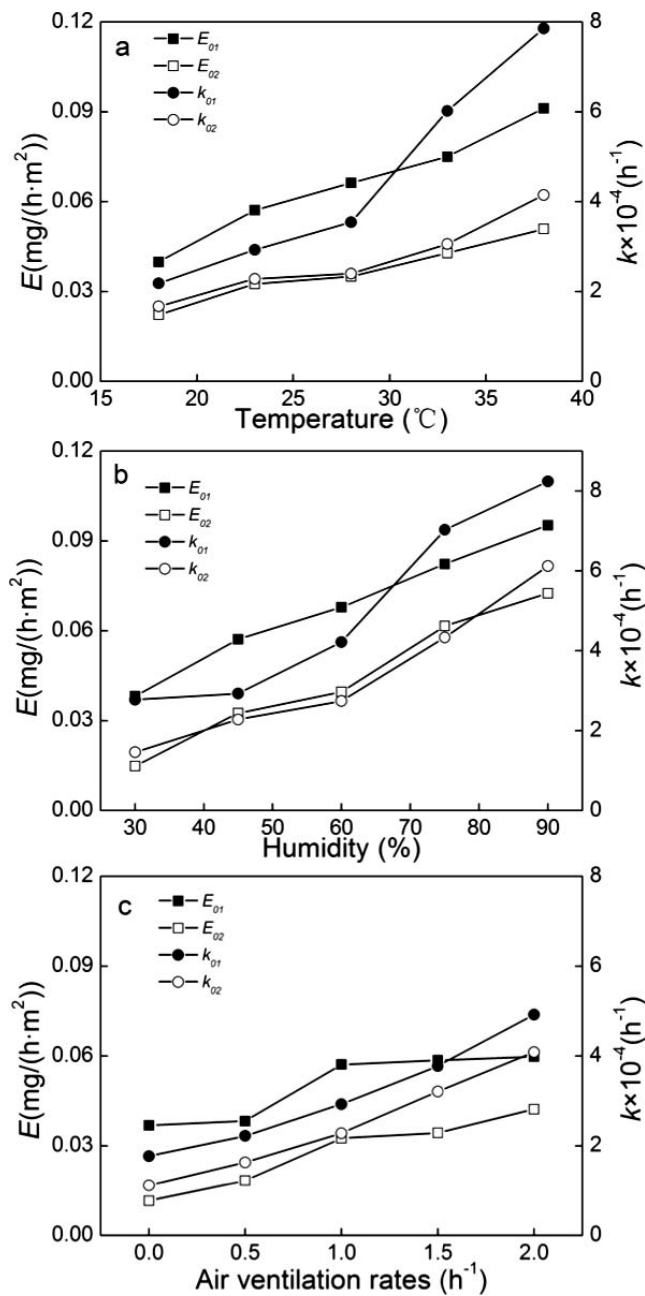

Figure 3.—Effect of environmental conditions on parameters of plywood's double exponential model. The specific experimental conditions of parts a through c are shown in Table 4.

ventilation rate, the formaldehyde equilibrium concentration for wood composites and the initial release rate will increase when all other things are equal. The studies of the influence of temperature (Myers 1984), relative humidity (Que and Furuno 2007), and ventilation rate (Groah et al. 1985) on formaldehyde emission from particleboard, plywood, and fiberboard are similar to this study. The main reason this occurs is that as the temperature increases, formaldehyde diffusion velocity increases, thus promoting the diffusion of plank interior formaldehyde molecules to the surface and increasing that the rate at which the formaldehyde molecules shift from the source phase to the air phase. As environment humidity increased,

the number of formaldehyde molecules dissolved in water vapor also increased. As a result, the formaldehyde concentration in the air also increased. Meanwhile, water molecules, in the air phase, compete with the formaldehyde molecules for adsorption sites on the surface of the wood composites, causing the stripping rate of the formaldehyde molecules to increase and thereby promoting formaldehyde emission. In addition, the increasing ventilation rate can cause a reduction in the formaldehyde concentration difference between the air and the source interface and thus cause an accelerating of the diffusion of the formaldehyde molecule to the air phase on the surface of the wood composites, promoting the diffusion of the
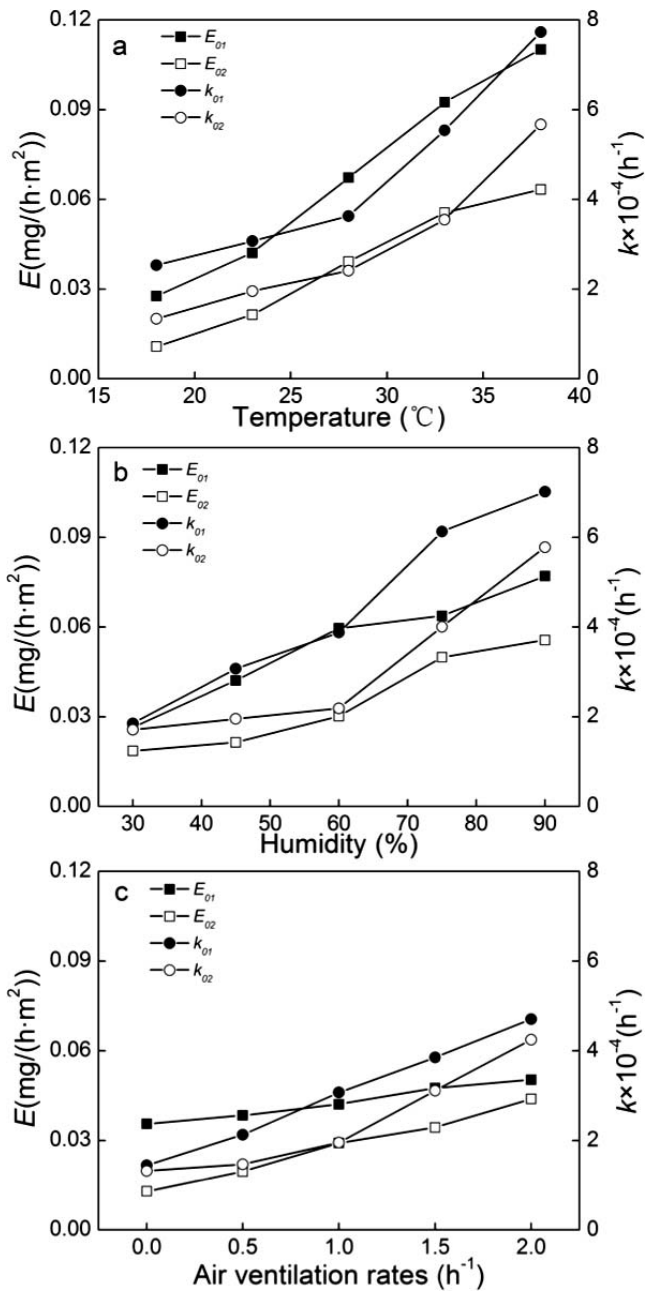
Figure 4.—Effect of environmental conditions on parameters of fiberboard's double exponential model. The specific experimental conditions of parts a through c are shown in Table 4.

Figure 5.—Measured concentration and the fitting result of formaldehyde emission model of particleboard. The specific experimental conditions of parts a through c are shown in Table 4.

formaldehyde molecules inside the wood composites to the surface.

By adding the physical characteristic parameters in Tables 1 through 3 to the predictive model formula (Eq. 6), the rules for releasing formaldehyde from wood composites can be predicted. In Figures 5 to 7, the solid line represents the predicted results, and the dotted line represents the experimental curves. Compared with the experimental test data, the maximum error of the simulation results was less than 15 percent, and it was linearly correlated with the experimental test data ($P < 0.05$). Moreover, th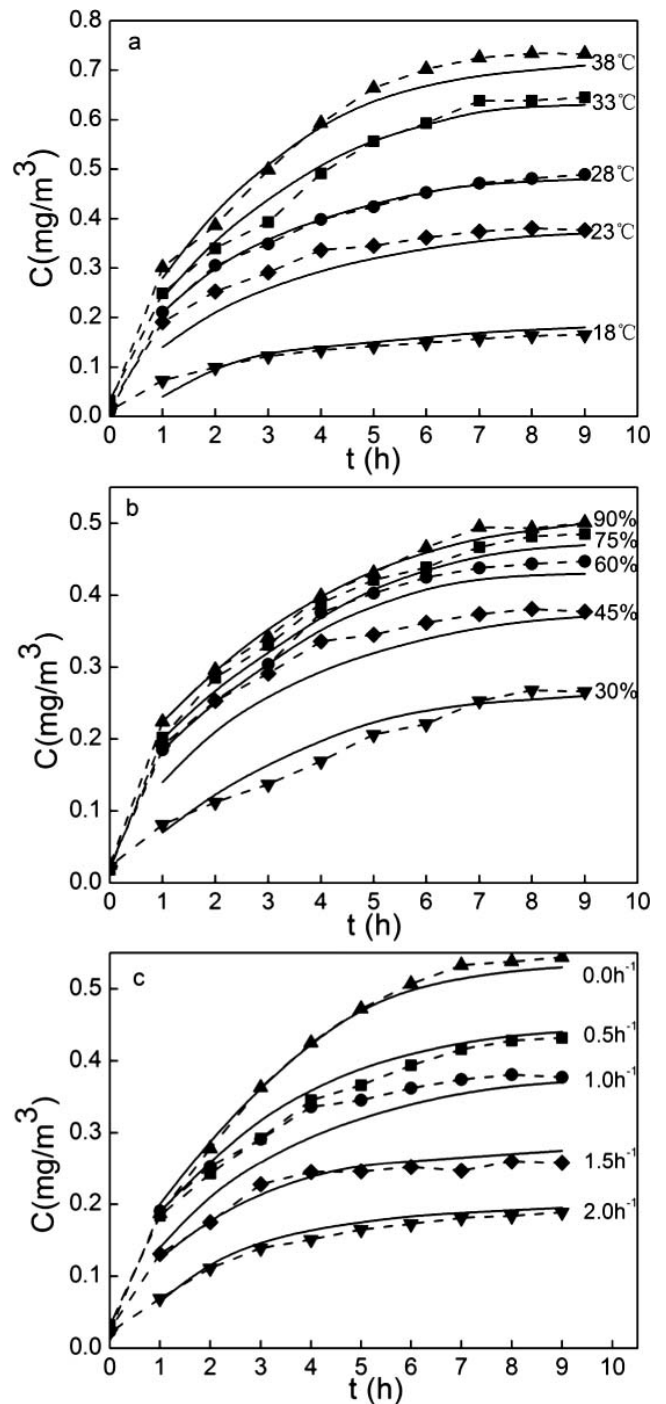is result indicates that the determination and calculation method used to model the release parameters described above is feasible.

Conclusions

This research has shown that a high-temperature or high-humidity environment will promote the emission of formaldehyde from wood composites. The process of emission of formaldehyde from wood composites can be
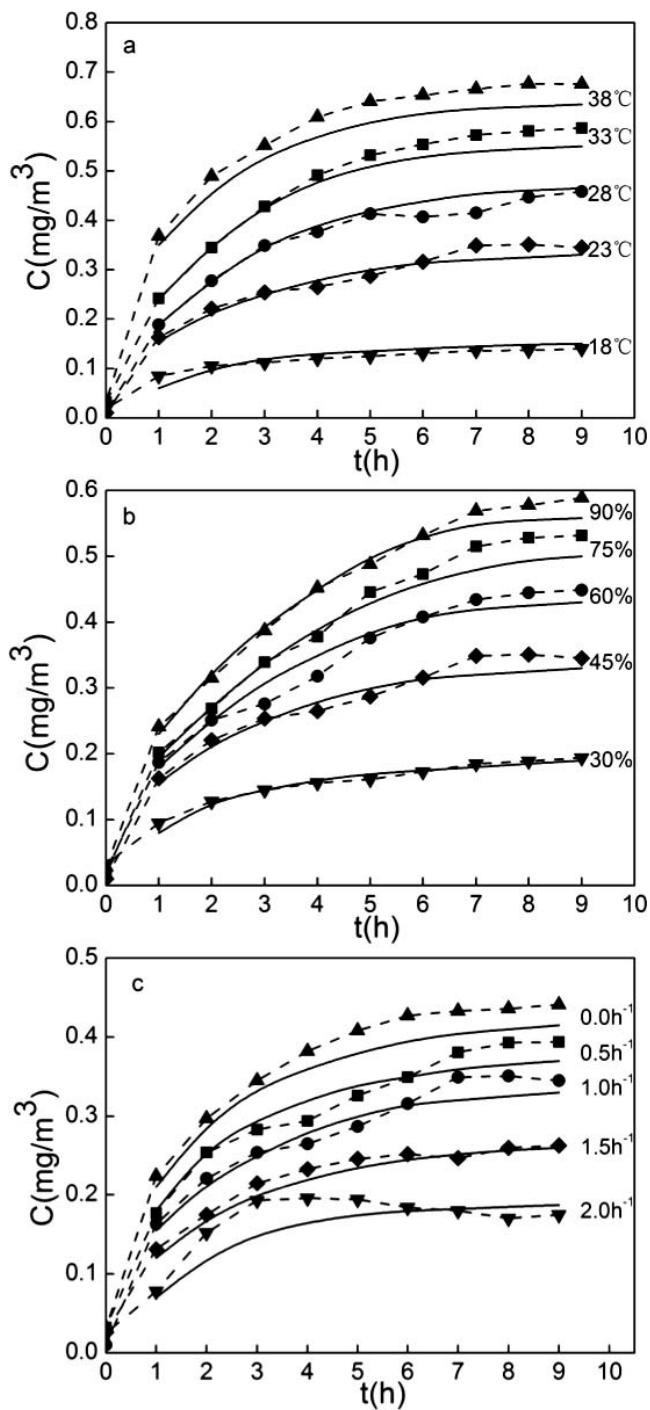
Figure 6.—Measured concentration and the fitting result of formaldehyde emission model of plywood. The specific experimental conditions of parts a through c are shown in Table 4.

Figure 7.—Measured concentration and the fitting result of formaldehyde emission model of fiberboard. The specific experimental conditions of parts a through c are shown in Table 4.

divided into the quick-release, slow-release, and release saturation phases. With increases in temperature and humidity or decreases in the ventilation rate, the release equilibrium concentration of formaldehyde from wood composites and the initial release rate will increase, resulting in a decrease in equilibrium time where all other things are equal. With an increase in environmental temperature and humidity or a decrease in ventilation rate,

the fast and slow initial formaldehyde transmission rates, E_{01} and E_{02}, and attenuation constants, k_{01} and k_{02}, will increase under certain experimental conditions. In addition, high temperature and high humidity are conducive to the improvement of the release rate of formaldehyde from wood composites, and the influence of the ventilation rate is relatively weak. Compared with experimental test data, the simulation results show a good fit and support the use

Table 1.—Parameters for the model of formaldehyde emission from particleboard.

Conditions[a]				Parameters[b]			
	M_0 ($\times 10^3$ mg/m^2)	C_{0s} (mg/m^3)	K	R^2	f	D ($\times 10^{-7}$ m^2/h)	h_g (m/h)
S	14.83	435.6	1,265.5	0.988	0.0167	6.13	0.00455
T (38°C)	23.21	535.1	834.7	0.876	0.0202	21.04	0.00454
T (33°C)	19.56	508.4	789.5	0.927	0.0186	17.38	0.00454
T (28°C)	16.03	486	1,116.4	0.885	0.0177	9.25	0.00455
T (18°C)	9.45	433.9	2,013.9	0.916	0.0163	4.34	0.00455
H (90%)	18.02	479.7	1,126.6	0.847	0.0199	8.17	0.00455
H (75%)	17.14	485.2	997.3	0.799	0.0165	8.04	0.00455
H (60%)	15.88	463.3	1,033.7	0.926	0.0183	7.06	0.00455
H (30%)	11.72	427.7	1,563.3	0.811	0.0188	5.99	0.00455
V (2.0 h^{-1})	15.98	455.3	1,237.8	0.932	0.0179	15.22	0.00455
V (1.5 h^{-1})	14.85	446.5	1,084.4	0.878	0.0176	12.45	0.00455
V (0.5 h^{-1})	14.77	431.8	1,009.1	0.998	0.0169	7.93	0.00455
V (0.0 h^{-1})	13.96	422.4	981.3	0.929	0.0166	4.11	0.00455

[a] S = standard conditions; T = temperature; H = humidity; V = ventilation rate.
[b] M_0 = the initial release concentration of formaldehyde from wood composites; C_{0s} = initial formaldehyde concentrations in wood composites; K = formaldehyde distribution coefficient between wood composites and air; f = dimensionless thickness correction factor; D = formaldehyde internal diffusion coefficient; h_g = mass transfer coefficient of formaldehyde in the air phase.

Table 2.—Parameters for the model of formaldehyde emission from plywood.

Conditions[a]				Parameters[b]			
	M_0 ($\times 10^3$ mg/m^2)	C_{0s} (mg/m^3)	K	R^2	f	D ($\times 10^{-7}$ m^2/h)	h_g (m/h)
S	14.22	347.7	1,382.4	0.988	0.0235	7.36	0.00455
T (38°C)	19.75	405.6	788.5	0.839	0.0267	23.24	0.00454
T (33°C)	18.63	388.3	881.3	0.876	0.0253	18.64	0.00454
T (28°C)	16.15	368.2	1,315.1	0.915	0.0239	10.12	0.00455
T (18°C)	10.02	333	2,993.3	0.937	0.0233	5.67	0.00455
H (90%)	17.54	379.7	1,058.2	0.774	0.0248	9.07	0.00455
H (75%)	17.32	355.6	1,200.4	0.845	0.0236	7.55	0.00455
H (60%)	14.37	343.8	1,351.4	0.926	0.0238	7.07	0.00455
H (30%)	10.78	307.1	1,879.2	0.791	0.0229	6.11	0.00455
V (2.0 h^{-1})	16.24	355.2	1,420.8	0.832	0.0236	16.27	0.00455
V (1.5 h^{-1})	13.57	336.3	1,385.5	0.935	0.0234	13.55	0.00455
V (0.5 h^{-1})	12.35	311.3	1,297.7	0.898	0.0231	8.37	0.00455
V (0.0 h^{-1})	10.06	299.8	1,151.6	0.792	0.0225	5.63	0.00455

[a] S = standard conditions; T = temperature; H = humidity; V = ventilation rate.
[b] M_0 = the initial release concentration of formaldehyde from wood composites; C_{0s} = initial formaldehyde concentrations in wood composites; K = formaldehyde distribution coefficient between wood composites and air; f = dimensionless thickness correction factor; D = formaldehyde internal diffusion coefficient; h_g = mass transfer coefficient of formaldehyde in the air phase.

Table 3.—Parameters for the model of formaldehyde emission from fiberboard.

Conditions[a]				Parameters[b]			
	M_0 ($\times 10^3$ mg/m^2)	C_{0s} (mg/m^3)	K	R^2	f	D ($\times 10^{-7}$ m^2/h)	h_g (m/h)
S	18.14	475.7	1,513.4	0.951	0.0158	5.54	0.00455
T (38°C)	25.36	563.3	806.5	0.639	0.0145	17.33	0.00454
T (33°C)	20.25	511.4	971.4	0.763	0.0156	14.16	0.00455
T (28°C)	17.24	485.5	1,421.1	0.886	0.0155	8.53	0.00455
T (18°C)	10.33	437	2,104.8	0.904	0.0164	3.69	0.00455
H (90%)	19.75	509.1	998.4	0.798	0.0133	8.10	0.00455
H (75%)	17.08	485.2	1,200.4	0.941	0.0148	7.75	0.00455
H (60%)	16.85	494.3	1,327.3	0.842	0.0151	6.76	0.00455
H (30%)	14.52	447.8	1,189.9	0.858	0.0174	4.56	0.00455
V (2.0 h^{-1})	17.37	475.3	1,322.5	0.779	0.0177	12.04	0.00455
V (1.5 h^{-1})	16.21	471.5	1,234.7	0.835	0.0163	9.77	0.00455
V (0.5 h^{-1})	15.04	452.9	1,182.3	0.901	0.0154	6.48	0.00455
V (0.0 h^{-1})	14.75	431.6	1,015.6	0.887	0.0122	3.89	0.00455

[a] S = standard conditions; T = temperature; H = humidity; V = ventilation rate.
[b] M_0 = the initial release concentration of formaldehyde from wood composites; C_{0s} = initial formaldehyde concentrations in wood composites; K = formaldehyde distribution coefficient between wood composites and air; f = dimensionless thickness correction factor; D = formaldehyde internal diffusion coefficient; h_g = mass transfer coefficient of formaldehyde in the air phase.

Table 4.—Overview of environmental chamber experiment.

Material (figure no.)[a]	Temperature (°C)	Relative humidity (%)	Ventilation rate (h^{-1})	Loading rate (m^2/m^3)
Particleboard (Figs. 2a and 5a), plywood (Figs. 3a and 6a), fiberboard (Figs. 4a and 7a)	18, 23, 28, 33, 38	45	1.0	1
Particleboard (Figs. 2b and 5b), plywood (Figs. 3b and 6b), fiberboard (Figs. 4b and 7b)	23	30, 45, 60, 75, 90	1.0	1
Particleboard (Figs. 2c and 5c), plywood (Figs. 3c and 6c), fiberboard (Figs. 4c and 7c)	23	45 ± 3	0, 0.5, 1, 1.5, 2	1

[a] Figure no. refers to the figures in this article.

of mathematical models to protect formaldehyde emissions from wood composites, and the maximum error of formaldehyde concentrations between predicted and measured was less than 15 percent.

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