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Research Paper

# Study on formaldehyde emissions from porous building material under non-isothermal conditions

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## HIGHLIGHTS

- The formaldehyde emissions in an ordinary particle board are simulated under non-isothermal conditions.
- Experiments demonstrating the emission of formaldehyde during floor heating and air circulation systems are carried out.
- The formaldehyde concentration in particle board is affected by thermal boundary condition.

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## ABSTRACT

Based on an improved model of formaldehyde emissions from building material under non-isothermal conditions, the mechanisms of formaldehyde emissions in dry porous building material are discussed. The formaldehyde emissions in an ordinary particle board are simulated under the different non-isothermal conditions, using floor heating and air circulation heating systems. The concentration of formaldehyde that remained in the board is strongly affected by the thermal boundary condition. Experiments demonstrating the emission of formaldehyde during floor heating and air circulation systems are carried out in a controlled environmental chamber. The experimental results validate the proposed model qualitatively. The present work showed that the equilibrium concentration in an airtight chamber having floor heating system is higher than that in an air circulation heating system.



## 1. Introduction

Porous building material, including medium density board, particle board and wood based floorboard, are widely used in interior decorations and as construction material. Exposure to formaldehyde can cause skin irritation, allergic reactions, and is a cancer hazard. Patients with long-term exposure to formaldehyde in building materials have shown symptoms of sick building syndrome (SBS) [1]. The adverse effects of formaldehyde on the indoor air quality (IAQ) is therefore of serious concern. In order to minimize the emission of formaldehyde from composite material made from urea-formaldehyde (UF) resins and phenol-formaldehyde (PF), emission norms were established in 1981 [2].

The transport of formaldehyde in porous building material has been an active area of research [3–5]. The understanding of various VOCs emission problems of building material under isothermal conditions [6,7] has been of particular interest. In the past few years in China, there has been an increasing demand for air circulation systems and radiant floor heating systems. These systems affect the VOCs migration process in a non-isothermal environment. In floor heating systems, the heat is transferred from the floor surface to other surfaces mainly by radiant heat transfer, which is different from air circulation systems that deliver heat from the air to the interior building material by convective heat transfer.

The thermal effect plays an essential role in the reduction of volatile organic compounds (VOCs) and other air pollutant emissions [8]. However, the effect of the non-isothermal condition on VOCs migration process has been considered to be almost negligible in most of the experimental and numerical studies. Only a few investigators have noticed that the non-isothermal condition is one of the key parameters that influence VOCs migration process from building material together with the initial conditions [9–12]. An et al. [13] experimentally studied the effect of room temperature on formaldehyde emission from floor material, such as laminate and plywood floorings, and furniture material, such as MDF and particle board veneered with decorative paper foil, by desiccator's method. Kang et al. [14] experimentally investigated the effect of bake-out on reducing indoor VOCs concentrations in a residential building unit with

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a radiant floor heating system. The effect of an elevated temperature on formaldehyde emissions from a wallpaper assembly, plywood flooring assembly, and particle board (as an example of furniture material) was studied in a small-scale chamber [14]. In Germany and the United States, large-scale test chambers were used for the evaluation of formaldehyde emissions [15]. Although the large-scale chamber method is very reliable, it is also time-consuming and expensive.

Due to a lack of accurate description of the coupled heat transfer and formaldehyde migration under non-isothermal conditions, the heat and mass transfer in porous building material have not been fully understood. Therefore, in this study, based on the coupled heat and formaldehyde migration model of porous building material [16], the coupled heat transfer and formaldehyde migration in an ordinary particle board is studied under the different non-isothermal conditions, using floor heating and air circulation heating systems. The transient temperature distribution in board and the formaldehyde diffusion behavior are compared between the air circulation system and the floor heating system. In addition, to validate the proposed numerical model, an experimental study on formaldehyde migration in chamber is conducted. The numerical model is compared to experimental results.

## 2. Model development

In Fig. 1, a schematic of the environmental chamber containing the test slab is shown. In order to simulate the effect of non-isothermal conditions, the temperature of the bottom layer of the board (heated by a floor heating system), or the temperature of the air in the chamber (heated by an air circulation heating system), is regulated by a constant temperature bath which varies from 25 °C to 65 °C.

### 2.1. Flux of thermodynamics

#### 2.1.1. Mass migration

The migration of formaldehyde and air in porous building material involves convection and diffusion. Under non-isothermal conditions, the migration flux of the air and formaldehyde is [16]:

$$\vec{J}_a = \rho_a \vec{u}_a - D_{ea} \nabla \rho_a \tag{1}$$

$$\vec{J}_V = \rho_V \vec{u}_V - D_{eV} \nabla \rho_V \tag{2}$$

In porous building material, it is assumed that there is no net air transfer between the building material and the environment. Therefore, the mass flux of the air $\vec{J}_a = 0$. The convection velocity of air is the same as that of formaldehyde vapor ( $\vec{u}_a = \vec{u}_V$ ). So Eq. (2) can be expressed as:

$$\vec{J}_V = \rho_V \left( \frac{D_{ea}}{\rho_a} \nabla \rho_a - \frac{D_{eV}}{\rho_V} \nabla \rho_V \right) \tag{3}$$

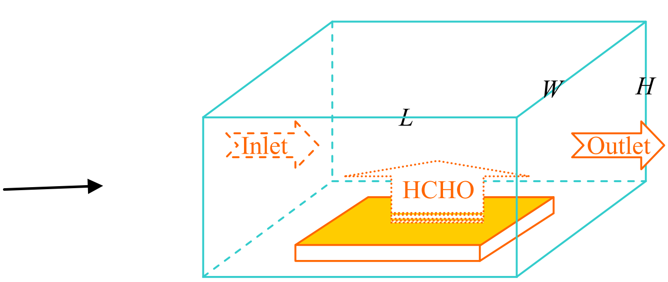


**Fig. 1.** Schematic of a simplified environmental chamber containing the test slab.

It is further assumed that the air and the formaldehyde obey the ideal gas law. Therefore,

$$\vec{J}_V = -\lambda_p \nabla P_V - \lambda_p^{11} \nabla T \tag{4}$$

where the infiltration coefficient $\lambda_p$ and thermal infiltration coefficient $\lambda_p{}^{11}$ are:

$$\lambda_p = \frac{\rho_V}{T} \left( \frac{D_{ea}}{\rho_a R_a} + \frac{D_{eV}}{\rho_V R_V} \right) \tag{5}$$

$$\lambda_p^{11} = \frac{\rho_V}{T^2} \left( \frac{D_{ea}(P - P_V)}{\rho_a R_a} - \frac{D_{eV} P_V}{\rho_V R_V} \right) \tag{6}$$

$D_{ea}$ is the effective diffusion coefficient of air (m$^2$/s) and $D_{eV}$ is the effective diffusion coefficient of formaldehyde vapor (m$^2$/s) in this paper, where $D_e$ is defined as the effective diffusion coefficient which includes the effect of adsorption on the surface of the porous material as well as the diffusion through pore air. As the porous building material are micro-porous medium, the effective diffusion coefficient $D_e$ can be written as [17]:

$$D_e = \frac{D_{atm} D_{kn}}{D_{atm} + D_{kn}} \tag{7}$$

where general molecular diffusion coefficient $D_{atm}$ and Knudsen diffusion coefficient $D_{kn}$ are:

$$D_{atm} = 4.942 \times 10^{-4} \varepsilon T^{1.5} / (P f_0) \tag{8}$$

$$D_{kn} = \frac{8 \varepsilon^2}{3 f_0 s_g} \left( \frac{2 R_V T}{\pi M_V} \right)^{0.5} \tag{9}$$

where $\varepsilon$, $T$, $P$, $f_0$, $S_g$, $R_V$ and $M_V$ are porosity, temperature, pressure, tortuosity factor, specific area for BET theory, gas constant and molecular weight of gas respectively.

#### 2.1.2. Heat transfer

Heat transfer in porous building material under temperature gradient involves heat conduction, infiltration convection heat transfer, radiation heat transfer and phase-change heat transfer [16]. Since the temperature difference between the material is not very large, the radiation heat transfer can be neglected. For the dry building material, the phase-change heat transfer also can be ignored. Therefore, the total heat flux $\vec{J}_q$ consists of conduction heat flux ( $\vec{J}_{qd}$ ) and convection heat flux ( $\vec{J}_{qc}$ ) caused by infiltration fluid flow:

$$\vec{J}_q = \vec{J}_{qd} + \vec{J}_{qc} = -(1-\varepsilon) k_s \nabla T + \varepsilon \left( \vec{J}_V h_v + \vec{J}_a h_a \right) \tag{10}$$

where $k_s$ is the effective thermal conductivity of the solid matrix of porous media. The enthalpies of the formaldehyde $h_V$ and air $h_a$ are described as:

$$h_V = C_{PV} T \tag{11}$$

$$h_a = C_{Pa} T \tag{12}$$

So the heat flux can be expressed as:

$$\vec{J}_q = -k_p \nabla P_V - k_T \nabla T \tag{13}$$

where the migration coefficient $k_p$ and apparent thermal conductivity $k_T$ are described as:

$$k_p = C_{PV} \rho_V \left( \frac{D_{ea}}{\rho_a R_a} + \frac{D_{eV}}{\rho_V R_V} \right) \tag{14}$$

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