Building and Environment 127 (2018) 98–106

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Modeling and controlling indoor formaldehyde concentrations in apartments: On-site investigation in all climate zones of China

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ARTICLE INFO

Keywords:
Indoor formaldehyde
Multiple regression model
Optimization

ABSTRACT

Formaldehyde has substantial adverse impacts on human health, and formaldehyde exposure primarily occurs in indoor environments. This study investigated the infiltration rates and indoor formaldehyde concentrations in 5 climate zones of China. In the winter, apartments in northern China suffer from higher indoor formaldehyde concentrations than apartments in southern China. The median indoor formaldehyde concentrations were 56 $\mu g/m^3$ (25%, 75%: 38, 91 $\mu g/m^3$) in northern China and 40 $\mu g/m^3$ (25%, 75%: 30, 61 $\mu g/m^3$) in southern China. There is a clear decrease in indoor formaldehyde concentrations in China. We also studied the relationships of the indoor air temperature, years of decoration, infiltration rate and source characteristic with formaldehyde concentrations in closed conditions. A multiple regression model that related these factors to the formaldehyde concentrations in closed conditions was constructed ($R^2 = 0.75$). The optimal curve for the suitable combination of temperature and infiltration rate to maintain low formaldehyde concentrations with the lowest cost was calculated for northern and southern China. By comparing the optimal curve and the state point of each city, we can infer the suitable tendency of indoor temperature and infiltration rate for each city. In Tianjin and Shenyang, apartments are overheating, thus causing a high percentage of some homes to have formaldehyde concentrations above the Chinese national standard. In Shanxi, Xinjiang, Yunnan and the Yangtze River Delta, the infiltration rate should be increased to some extent to achieve better indoor air quality. In Hunan, Hubei and Chongqing, indoor temperatures could be increased to improve indoor thermal comfort.

1. Introduction

Currently, people spend more than 90% of their time indoors and experience adverse health effects resulting from exposure to indoor pollutants. Formaldehyde, which is one of the most ubiquitous and well-known indoor pollutants, can cause acute discomfort for humans. The critical acute effects of formaldehyde exposure are eye and nasal irritation [1]. Lang and Bruckner [2] found that minimal objective eye irritation was observed at a formaldehyde level of 0.5 ppm with peaks of 1 ppm. Formaldehyde can also have chronic adverse health effects on humans, such as asthma and chronic bronchitis [3–5]. In addition, formaldehyde is expected to be related to a significant cancer risk [6,7] and is considered carcinogenic to humans by the International Agency for Research on Cancer [8]. To prevent adverse health effects from formaldehyde exposure, the WHO and Chinese national indoor air quality standard recommended a guideline of 0.1 mg/m^3 [9,10]. Many studies have re-evaluated the WHO (2010) formaldehyde indoor air quality guideline. They concluded that this guideline had not been challenged by recent studies and could be considered preventive of carcinogenic effects, as well as acute and chronic sensory irritation in the airways [11–13].

Formaldehyde exposure in indoor environments is high due to the presence of strong formaldehyde sources in these environments [14,15]. Wood-based materials, particle board and flooring materials are typical indoor formaldehyde sources [16–18]. Recent studies reviewed investigations of indoor formaldehyde concentrations in Chinese apartments over the past 15 years and found that many apartments that had been decorated or renovated within the past year cannot satisfy the Chinese national indoor air quality standard and the WHO guideline [19,20], indicating serious formaldehyde pollution for new apartments in China. Most of these investigations focused on formaldehyde pollution in new apartments. However, studying the indoor formaldehyde concentrations in apartments that have been decorated for some years is of importance. In addition, most investigations were conducted after apartments had been closed for 12 h. Although this is a standard condition that is required in the Chinese national indoor air quality standard and is a good approach for determining the real exposure when people sleep [20], investigating formaldehyde

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http://dx.doi.org/10.1016/j.buildenv.2017.10.036
Received 12 September 2017; Received in revised form 12 October 2017; Accepted 29 October 2017

concentrations under normal ventilation conditions is also important for determining peoples actual formaldehyde exposure during the day.

Moreover, studying the emission characteristics of formaldehyde sources is also important for finding good strategies to protect against formaldehyde exposure. Many researchers have studied the emission characteristics of formaldehyde. Xu and Zhang [21] investigated the impact of relative humidity on formaldehyde diffusion. They tested formaldehyde concentrations under different relative humidity levels, 25%, 50% and 80%, and they concluded that there is no distinguishable difference in the effective diffusion coefficient of formaldehyde when the relative humidity is between 25% and 50%. Zhang et al. [22] studied the effect of air temperature on formaldehyde emissions. They determined that air temperature had a significant impact on the diffusivity of formaldehyde. Recently, Liang et al. [23] presented a model to describe the combined effects of temperature and humidity on formaldehyde emissions. However, given the complex conditions in real apartments, the chamber study typically does not work well for long-term evaluation [20]. A suitable approach for studying the emission characteristics of formaldehyde in real apartments is to use a regression method to separate the effects of different factors [24]. Based on the regression model, we can find optimal combinations of parameters that can maintain low indoor formaldehyde concentrations with the lowest cost. By comparing the optimal combinations with the current state of infiltration rate and indoor temperature in each zone, we can determine a suitable tendency to achieve low indoor formaldehyde concentrations with the lowest cost.

The objectives of this paper are (i) to investigate the current levels of indoor formaldehyde concentrations in all climate zones of China; (ii) to determine the differences between indoor formaldehyde concentrations in closed conditions and daily conditions caused by the lifestyles of residents in different zones; (iii) to create a reliable model that shows the comprehensive effects of different factors, including indoor air temperature, years of decoration and infiltration rate, on the indoor formaldehyde concentrations in closed conditions; and (iv) to determine a suitable tendency for each zone to achieve low indoor formaldehyde concentrations with the lowest cost.

2. Methods

2.1. Sampling locations and conditions

The study was conducted from Nov. 15, 2016, to Feb. 15, 2017. The formaldehyde concentrations in the bedrooms of apartments, indoor air temperatures and infiltration rates were investigated in a total of 279 apartments in nine zones of China. The locations of these zones are shown in Fig. 1. These zones cover five climate zones of China. Table 1 lists the basic information of the tested apartments.

We investigated the indoor formaldehyde concentrations under two conditions. First, all of the windows and doors in each apartment had been closed for more than 12 h before and during sampling. This is a standard method for investigating indoor formaldehyde concentrations in the worst conditions according to the Chinese national guideline GB/T 18883-2002 [10]. We call this condition the closed condition, and it could be useful for predicting formaldehyde exposure during the night because many Chinese residents tend to close their windows while they sleep [20]. To investigate the exposure level during the daytime, we also measured the indoor formaldehyde concentrations in daily conditions, where the investigation was conducted without any intervention, e.g., without changing the status of windows and doors before and during the investigation.

2.2. Measurement of formaldehyde

The formaldehyde concentration was measured by visible spectrophotometry using the 3-methyl-2-benzothiazolinone hydrazone method. Formaldehyde was sampled at 0.5 L/min for 20 min and was absorbed into the absorption liquid and oxidized by ferric ion in an acidic medium to generate a blue-green compound. The darkness of this compound was measured by visible absorption at 630 nm and was used to calculate the formaldehyde concentration in the air. The recovery of formaldehyde ranged from 93% to 101%, and the detection limit was 0.056 μg. The relative standard deviations for the corresponding measurements were less than 5%. The Chinese national standard GB/T 18204.2–2014 [25] provides more information about this method. This method has been used in many studies and provides acceptable accuracy [24,26].

2.3. Measurement of infiltration rate

The infiltration rate was determined using the CO_2 decay method. Prior to the measurement, all of the doors and windows were closed, and CO_2 was injected into the middle of the room until the concentration was higher than 2500 ppm. A fan was used to mix the air and CO_2 to achieve a uniform distribution. Then, the CO_2 concentration was continuously monitored. Because CO_2 is an inert gas, the infiltration rate can be calculated using equation (1):

$$V_i = \frac{\ln(C_1 - C_0) - \ln(C_t - C_0)}{t} \tag{1}$$

where V_i is the infiltration rate of the room, h^{-1}, C_1 is the initial CO_2 concentration in ppm, C_t is the final CO_2 concentration in ppm, C_0 is the outdoor CO_2 concentration in ppm, and t is the duration of the measurement in h.

2.4. Regression model

Traditional studies about the effect of temperature on emissions of formaldehyde were conducted with constant relative humidity. These studies found that emissions of formaldehyde from building materials were positively correlated with temperature. Xiong and Zhang [27] found that the initial emittable concentration increased by approximately 507% when the temperature increased by 25.4°C. Wiglusz et al. [28] studied the emissions of formaldehyde from laminate floorings at different temperatures. Formaldehyde emission was not detected at 23°C and 29°C, but it increased significantly at 50°C for one type of material. Thus, it is reasonable to infer an exponential increase in formaldehyde emissions with temperature. Spearman's rank correlation coefficient in Table 2 also verifies that this assumption is reasonable.

Humidity is another factor that may influence formaldehyde emissions. Myers and Nagaoka [29] found that formaldehyde emissions from a urea-formaldehyde (UF)-bonded particleboard increased 2-fold from 30% to 75% relative humidity at an acceptable temperature (25°C). However, Spearman's rank correlation coefficient between formaldehyde concentrations and relative humidity is negative in our study (Table 2), which is in contrast with the results of chamber studies. This result occurs because the impact of relative humidity (RH) is very low compared with other factors in real apartments [24]. Therefore, we ignored the impact of relative humidity in our regression model.

Gilbert et al. [30] found that ventilation effectively decreased indoor formaldehyde concentrations; thus, infiltration is the main way to remove indoor formaldehyde in closed conditions. Given that the outdoor formaldehyde concentration is low and can be ignored [31], we infer that the indoor formaldehyde concentrations will decay with increasing infiltration rate at a logarithmic rate. Moreover, Sakai et al. [32] found a significant negative correlation between logarithm-transformed indoor formaldehyde concentrations and building ages. Thus, we infer that the indoor formaldehyde concentrations also decay with the years of decoration at a logarithmic rate in our study.

To determine the extent to which indoor formaldehyde concentrations are affected by these factors after a living space has been decorated, as well as the comprehensive effect of these factors on indoor formaldehyde concentrations, we constructed a multiple regression