Atmospheric Environment 122 (2015) 561–568

Contents lists available at ScienceDirect

Atmospheric Environment

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

Source emission and model evaluation of formaldehyde from composite and solid wood furniture in a full-scale chamber

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HIGHLIGHTS

- HCHO emissions were measured from different furniture in a full-scale chamber.
- The effect of ventilation rate on formaldehyde emissions was studied.
- The power-law decay model fits the data better than the first-order decay model.
- Experimental data and model parameters are needed for emission models.

ARTICLE INFO

Article history:
Received 27 February 2015
Received in revised form
11 September 2015
Accepted 23 September 2015
Available online 28 September 2015

Keywords:
Formaldehyde
Emissions from furnishings
Source emission model
Full-scale chamber
First-order decay model
Power-law decay model

ABSTRACT

This paper describes the measurement and model evaluation of formaldehyde source emissions from composite and solid wood furniture in a full-scale chamber at different ventilation rates for up to 4000 h using ASTM D 6670-01 (2007). Tests were performed on four types of furniture constructed of different materials and from different manufacturers. The data were used to evaluate two empirical emission models, i.e., a first-order and power-law decay model. The experimental results showed that some furniture tested in this study, made only of solid wood and with less surface area, had low formaldehyde source emissions. The effect of ventilation rate on formaldehyde emissions was also examined. Model simulation results indicated that the power-law decay model showed better agreement than the first-order decay model for the data collected from the tests, especially for long-term emissions. This research was limited to a laboratory study with only four types of furniture products tested. It was not intended to comprehensively test or compare the large number of furniture products available in the market place. Therefore, care should be taken when applying the test results to real-world scenarios. Also, it was beyond the scope of this study to link the emissions to human exposure and potential health risks.

1. Introduction

Formaldehyde (HCHO) has been of concern as an indoor air pollutant because it exists in a wide range of products and human exposure to it may result in adverse health effects. Acute and chronic inhalation exposures to formaldehyde in humans, particularly children, can result in respiratory symptoms and irritations of the eyes, nose, and throat (McGwin, Jr. et al., 2010). The U. S. Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC) have classified formaldehyde as a probable human carcinogen (EPA, 1989; IARC, 1995) and the U. S. National Toxicology Program (NTP, 2014) recently classified formaldehyde as a known human carcinogen. Exposure to formaldehyde may be linked to nasopharyngeal cancers and leukemia (Agency for Toxic Substances and Disease Registry, 2010). Formaldehyde is released into homes from a variety of indoor sources, e. g., wood products, consumer products, coatings, permanent-press fabrics, insulation materials, combustion appliances, and tobacco products (Salthammer et al., 2010). It may also be formed by the chemical reaction of ozone with volatile organic compounds (VOCs) that are present indoors (Liu et al., 2004). The most

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http://dx.doi.org/10.1016/j.atmosenv.2015.09.062
1352-2310/Published by Elsevier Ltd.

significant sources of airborne formaldehyde in homes and buildings are composite wood products (CWPs), such as furniture and cabinets that are made with urea - formaldehyde resin, including hardwood plywood (HWPW), particleboard (PB), and medium density fiberboard (MDF). Various factors have significant effects on the levels of formaldehyde indoors, including temperature, humidity, and ventilation rate.

The EPA is currently evaluating the potential health effects of formaldehyde exposure through the Integrated Risk Information System (IRIS) Program (EPA, 2013). EPA initiated this research study to better inform the potential exposures to formaldehyde in composite wood products that are used in the construction of new homes, the renovation of existing homes, and in various furnishings and consumer products (EPA, 2011). The Formaldehyde Standards for Composite Wood Products Act (S.1660), signed by U. S. President Obama on July 7, 2010, requires the EPA to promulgate regulations to implement standards to limit formaldehyde emissions from CWPs. These activities emphasize EPA's interest in formaldehyde exposures and the need to understand indoor sources of formaldehyde through improved understanding of source emissions and the factors that affect its indoor fate and transport.

Source emissions of formaldehyde have been studied for decades. Most of the studies were summarized in the review paper prepared by Salthammer et al. (2010). Source emission modeling is an important component of an overall formaldehyde exposure assessment. A few source emission models have been developed (Guo, 2002) for formaldehyde releases from composite wood products. They can be classified as empirical models (such as the first-order decay model, the double-exponential decay model, and the power-law decay model) or as mass transfer models based on mass balances. Matthews and colleagues at the Oak Ridge National Laboratory developed a model in the late 1980s to predict the formaldehyde concentrations that result from steady state off-gassing from composite wood products in residences (Matthews, 1987; Hawthorne and Matthews, 1987). The model, in accordance with Fick's first law of diffusion, assumes a linear relationship with a negative slope exists between the formaldehyde emission factor and the steady state, gas-phase concentration of formaldehyde. The model was applied previously to investigate the impact of indoor temperature and relative humidity (RH) on the formaldehyde concentration resulting from one emitter in a single compartment (Matthews et al., 1986, 1987). Matthews' model was validated by researchers at the National Institute of Standards and Technology (NIST) (Silberstein et al., 1988).

Mass transfer-based diffusion models have been developed by various researchers to describe the VOC emissions, including formaldehyde, from building materials (Little et al., 1994; Cox et al., 2002; Huang and Haghighat, 2002; Kumar and Little, 2003; Haghighat and Huang, 2003; Xu and Zhang, 2004; Wang and Zhang, 2010). The key parameters of these models include diffusion coefficients, partition coefficients, and initial chemical concentrations in the solid materials. Diffusion models could be used to predict formaldehyde emissions from composite wood products. However, the main obstacle to using these models is the lack of experimental data for the requisite physical parameters (Xiong et al., 2008, 2011a,b). It appears that there are no such data for composite wood products that are used for finished goods, and parameter data for formaldehyde in building materials are quite limited.

In this study, we investigated formaldehyde source emissions from composite and solid wood furniture for up to 4000 h. The four types of furniture products were each tested in a full-scale chamber by measuring the formaldehyde gas phase concentrations over a range of ventilation rates. The data were used to calculate the emission factors of formaldehyde and to assess the applicability and fit of first-order decay, power-law, and the Matthews formaldehyde source emission models. These models are commonly used to predict formaldehyde concentrations in residences due to the presence of composite wood products.

2. Materials and method

Four types of furniture products were tested for up to 4000 h in this study. A full-scale, indoor air quality environmental test chamber, with a volume of approximately 30 m^3, was used to conduct the tests. The full-scale chamber provides controlled conditions of loading, temperature, humidity, and air change rate that are typical in the indoor environment. The details of the chamber were described elsewhere (Liu et al., 2004).

2.1. Test products

The products to be tested were purchased from local retail stores (Table 1). They were selected based on emission concentration information collected from the literature (Environment California Research and Policy Center, 2008) and the availability of the products on the market. While it was not our intention to obtain statistically representative products for the entire U.S. market, efforts were made to select products with anticipated high, medium, and low formaldehyde emissions. When the products were received at the laboratory, product information was recorded in the project's laboratory notebook. The information recorded included the name of the product, the date of purchase, manufacturer, lot number, and condition upon arrival. Each box of products was then wrapped completely with one layer of aluminum foil and placed in a Tedlar bag to prevent cross contamination. The products were stored in the room where the full-scale chamber was located at 23 ± 2 °C, 50 ± 5% RH, and 5 h^{-1} air change rate. The furniture was taken from its packaging, assembled outside the full-scale chamber as quickly as possible (<6 h) and transferred to the chamber for the tests.

2.2. Chamber testing

The tests were conducted at 23 ± 0.5 °C, 50 ± 2% RH, and different air change rates (Table 2). Tests T1, T2, T3, and T4 were performed with the same type of furniture and the same source loading under various air change rates with T2 being a replicate test of T1. The chamber tests followed ASTM D 6670-01 (2007). The sampling diagram is shown in Fig. 1. The test furniture was placed in the center of the chamber floor. A mixing fan mounted to the ceiling of the chamber ceiling and forcing air toward the upper right corner of the chamber was turned on for all the tests. The tests lasted for 5 days or longer. Gas phase formaldehyde was collected on a dinitrophenylhydrazine (DNPH) silica-gel cartridge (Waters, Sep-Pak) at the elapsed times of 1, 2, 4, 8, 24, 48, 72, 96, 168, 217, 264, and 336 h or longer at three locations, i.e., 3 ft (0.91 m) and 5 ft (1.52 m) above the chamber floor and at the exhaust of the chamber. All samples were collected simultaneously via sampling lines that passed through the top of the chamber, with one sampling port being adjustable for duplicate samples (C3). Background samples were collected prior to the experiment without a test specimen in the chamber. SF_6 was injected periodically and monitored by on-line gas chromatography with electron capture detector (GC-ECD) to determine the air change rate. During the tests, the environmental conditions in the chamber were monitored, including temperature, pressure, and RH.