MODELING THE EFFECTIVENESS OF FLUSH-OUT PROCEDURES IN REDUCING FORMALDEHYDE IN NEW BUILDING CONSTRUCTION

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ABSTRACT: New building construction is often a source of indoor air pollution due to the large amount of volatile organic compounds that are emitted from newly manufactured building materials as well as field applied coatings, sealants and adhesives. One major concern has been the release of formaldehyde (HCHO). High levels of HCHO exposure has been linked to negative health effects such as irritation of the skin, eyes, nose and throat, neurological effects, increased risk of asthma and possibly the development of cancer. The United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) rating system attempts to encourage through voluntary action sustainable building design and construction practices. LEED recommends a whole building flush-out procedure and indoor air quality assessment to occur for all new construction to help reduce indoor air pollutant concentrations. The LEED version 4 rating system procedure requires that 4267 m^3 of outside air to be supplied to the interior for every square meter of floor area. This research explores the effectiveness of the flush-out procedure and the inferred limits to the amount of off-gassing materials that can be included in new construction. The project used a first order emission decay model to iteratively determine the maximum allowable source emitting areas that could be present at the start of the flush-out procedure and still meet recommended concentration limits for formaldehyde from two engineered wood products. Modeling included residential, school and office scenarios to determine a range of allowable source areas (0.25 m^2 to 1.60 m^2 per unit of floor area). These results varied with changes in air exchange rates, material emissions characteristics and ceiling heights. In most cases the modeled indoor air concentration of formaldehyde was calculated to be below the recommended limit when using typically expected source areas in each of the three scenarios.

KEYWORDS: indoor air quality, flush-out, formaldehyde, LEED, modeling

1.0 INTRODUCTION

1.1 Flush-out

New building construction is often a source of indoor air pollution due to the large amount of volatile organic compounds that are emitted from newly manufactured building materials as well as field applied coatings, sealants and adhesives. One major concern has been the release of formaldehyde (HCHO). High levels of HCHO exposure has been linked to negative health effects such as irritation of the skin, eyes, nose and throat, neurological effects, increased risk of asthma and possibly the development of cancer (ATSDR 2008). The United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) rating system attempts to encourage through voluntary action sustainable building design and construction practices. LEED recommends a whole building flush-out procedure and indoor air quality assessment to occur for all new construction to help reduce indoor air pollutant concentrations. The LEED version 4 (LEEDv4 2013) rating system procedure requires that 4267 m^3 of outside air to be supplied to the interior for every square meter of floor area.

1.2 Recommended Limits

To evaluate the effectiveness of flush-out procedures for indoor air quality LEEDv4 sets a maximum indoor air concentration of 27 ppb (33 $\mu g/m^3$) for formaldehyde at the end of the flush-out period that can be measured using a time-weighted average sample (ASTM D5197-09). The National Institute for Occupational Safety and Health (NIOSH) states a recommended exposure limit (REL) of 20 $\mu g/m^3$ (NIOSH 1997) and the California Department of Public Health in their 2010 Standard Method for Testing and Evaluation of VOC Emissions (CDPH method v1.1) has a recommended limit of 9 $\mu g/m^3$. Typical outdoor air concentrations of formaldehyde are cited in the literature to be lower in rural settings and higher in urban settings with concentrations ranging from 1 to 68 ppb (USDHHS 1999). One study provided an average across all outdoor areas as 8.3 ppb (10.2 $\mu g/m^3$) (Shah and Singh 1988).

1.3 Formaldehyde Sources

Flush-outs are intended to reduce indoor air pollutant concentrations by bringing in fresh air and exhausting pollutant laden building air that can have exceptionally high concentrations in the first few weeks after material installation due to elevated emissions rates that often occur with newly manufactured building materials and furniture (NPI 1999, Xiong et al. 2011). New building construction often utilizes recently manufactured engineered wood products that contain VOCs such as formaldehyde that are used in the manufacturing process to bond smaller wood pieces into larger wood products (Salthammer et al. 2010) such as particleboard (PB) and medium density fiberboard (MDF). These wood products often continue to off-gas VOCs for an extended period of time and are a concern regarding long term indoor pollutant concentrations. Some studies researching the time varying aspect of these emission rates have been performed for both short term and long term decay rates. These studies have experimentally documented higher emissions rates of formaldehyde at the beginning of newly manufactured engineered wood products that have had good correlation with first order decay models (Brown 1999). Although second order and double exponential decay models exist they appear to mainly correct long term emission rates well past the time period that would be used for a building flush-out. Other emission rate models for formaldehyde instead of being directly time dependent are dependent on the indoor air pollutant concentration. They utilize the assumption that increased indoor air pollutant concentrations create a back pressure effect that reduced the emission rate (Guo 2002 and Mathews et al., 1987). Since the intent of a flush-out is to reduce the concentration via high air exchange rates the back pressure model may not be well suited since at high air exchange rates, the resultant low pollutant concentrations should reduce back pressure and thereby produce an increase of emission rates over time rather than a decrease. Thus, to take into account higher initial emissions expected in new construction this project implemented a time varying solution using a first order decay emission model.

Typical engineered wood such as PB and MDF can be readily found in new construction products such as doors, cabinetry and furniture that are most often installed at the end of the construction period to reduce the chance for damaging finishes. Although many other wood products are used in the construction process many of these are subsequently covered by other construction materials and the exposed surface area of these wood products are not generally in contact with the majority of the indoor air. Thus, this project examined PB and MDF as the primary element for wood based HCHO emissions in new construction.

2.0 METHDOLOGY

2.1 General Solution

This project studied the time varying solution of formaldehyde concentrations due to emission from PB and MDF installed in new building construction. Using λ as the air exchange rate (h^{-1}), EF as the emissions factor ($\mu g/m^2$-h), A as the exposed surface are of the source emitting material (m^2), C_{out} as the ambient outdoor formaldehyde concentration ($\mu g/m^3$), V as the volume (m^3) and C as the indoor air formaldehyde concentration ($\mu g/m^3$), the equation for the change in formaldehyde concentration with respect to time can be expressed as shown in Eq. 1:

$$\frac{dc}{dt} = \lambda C_{out} + EF \times \frac{A}{V} - \lambda C \qquad [1]$$

If sources and losses are grouped as $S(t) = \lambda C_{out} + EF \times \frac{A}{V}$ and $L(t) = \lambda$ then the equation can be more simply written as shown in Eq. 2:

$$\frac{dc}{dt} = S(t) - L(t)C(t) \qquad [2]$$

By multiplying Eq. 2 on both sides by an integrating factor, $\mu(t)$ where $\mu(t)L(t) = \mu'(t)$ this can be solved as a first order differential equation with the general solution form shown in Eq. 3:

$$C(t) = \frac{\int \mu(t)S(t)dt + c}{\mu(t)} = \frac{\int e^{Lt}S(t)dt + c}{e^{Lt}} \qquad [3]$$

Where c is the constant of integration which can be determined via an initial value problem.

2.2 Decay Rate

Brown stated the first order decay model for the emission factor as shown in Eq. 4:

$$EF = k_1 M_0 e^{-k_1 t} \qquad [4]$$

Brown provided results from experiments for particle board and MDF to derive the emission factor parameters k_1 and M_0. Where k_1 is the decay rate and M_0 is the total emittable mass of pollutant per unit area of product surface at $t=0$. Taking an average of these parameters from Brown's three MDF experiments such that $k_{1,MDF}$ = 0.00062 h^{-1} and $M_{0,MDF}$ = 650,000 μg/m^2 and from the three particle board experiments such that $k_{1,PB}$ = 0.0014 h^{-1} and $M_{0,PB}$ = 346,667 μg/m^2 the average parameters are used in modeling the emissions of formaldehyde in new building construction. By substituting the first order decay model of EF into the time varying solution the expanded general solution is determined as shown in Eq. 5:

$$C(t) = \frac{\int e^{\lambda t}(\lambda C_{out} + (k_1 M_0 e^{-k_1 t}) \times \frac{A}{V})dt + c}{e^{\lambda t}} \qquad [5]$$

2.3 Flush-out Duration

The LEEDv4 indoor air quality assessment criteria requires that 4267.2 m³ of outdoor air be supplied per square meter of gross floor area and uses the CDPH method for testing and evaluating VOC emissions from indoor sources. The duration of the flush-out procedure is directly related to the air exchange rate by:

$$T_r = \frac{V_r}{V_f \times \lambda} \qquad [6]$$

Where T_r is the time duration (in hours) required to meet the volume of air required (V_r = 4267.2 m^3) at a given air exchange rate and unit volume (V_f = the one square meter of floor multiplied by the ceiling height). Dimensions including ceiling heights of reference spaces are provided in the CDPH emission testing method. By using the first order decay model parameters and applying $V = V_f$ an initial value problem can be formed with the assumption that $C(0) = C_{out}$ = 10.2 μg/m^3 to determine the constant of integration. Having found the constant of integration all parameters of Eq. 5 are known and by setting $C(T_r) = C_{max}$ = 33 μg/m^3 the maximum allowable area of source emitting material can be determined.

2.4 Iterative Solver

Calculation of the allowable areas was accomplished using an iterative numerical solver coded in MATLAB R2013a that started with an initial guess for the source emitting area parameter, solved for the indoor air concentration for time steps starting at t=0 to $t=T_r$ and then strategically adjusted the area parameter so that the indoor air concentration at the end of the flush-out procedure would be equal to C_{max}. Air exchange rates were then incrementally increased starting at 0.5 h^{-1} up to 16 h^{-1} and the iterative procedure for finding the maximum source area was repeated at each air exchange rate. The range of exchange rates selected was meant to reflect values that could be achieved given a wide range of mechanical ventilation capabilities. Although an air exchange rate of 16 h^{-1} is very high and unreasonable for a residential scenario, commercial laboratories are often designed to have the capacity to perform 8 to 12 air changes per hour. Fig. 1 provides a flow chart of the steps used in the MATLAB code.

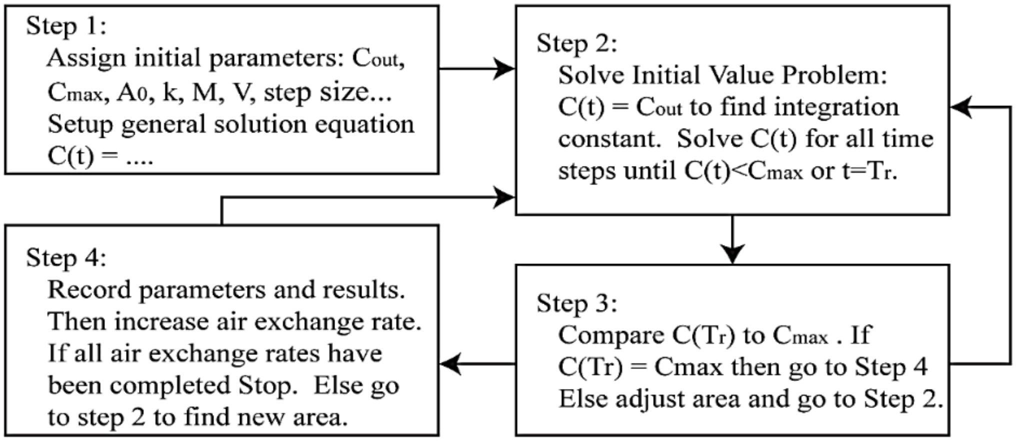

Figure 1: Four-step flow chart of solver used to find allowable source area.

2.5 Scenarios

The CDPH (2010) emission testing method includes three scenarios for indoor air quality modeling. These are a standard school classroom, a standard private office and a new single family residence. Although multiple parameters exist for each of the scenarios, only the ceiling heights are needed to update Eq. 5 to solve for the maximum allowable area of source emitting material. The school classroom and single family residence scenarios both have ceiling heights of 2.59 m and the private office scenario has a ceiling height of 2.74 m. The scenarios also include standard product quantities such as the area of doors and millwork that are typically expected in these spaces and may be sources of pollutant emissions. By selecting the quantities that are related to MDF and particle board and dividing them by the floor area in each scenario the maximum allowable source areas can be compared to the source areas that are expected.

3.0 RESULTS & DISCUSSION

3.1 Air Exchange and Source Areas

Table 1 shows the maximum allowable source emitting area that can be present at the beginning of the flush-out procedure such that at the end of the flush-out period the concentration will be less than or equal to the maximum permissible limit of 33 μg/m³ for each of varying air exchange rates. It is important to note that for each scenario the results are shown per square meter of floor area. Thus, although the floor area of the CDPH new single-family residence scenario lists a 211 m² floor area and a 547 m³ volume the analysis and results presented attempts to volume normalize the results. It is apparent in Table 1 that higher air exchange rates allow for larger areas of source emitting materials to be present while still meeting the maximum permissible level at the end of the flush-out duration.

Fig. 2a is a line plot of Table 1 values and shows a relatively linear relationship between air exchange rates and allowable source areas when using MDF. Fig. 2b is the same data as Fig. 2a except plotted with the x-axis on a log-scale. Fig. 4 is a line plot of air exchange rates and allowable source areas when using particle board. Because the office scenario has a larger volume of 2.74 m³ per square meter of floor area compared to the school and residential scenarios (V=2.59 m³) the office scenario has higher allowable areas starting when air exchange rates are above 3/h. This difference though is relatively small and would be expected given the minor change in volume. Fig. 3a is a line plot of the indoor air formaldehyde concentrations over time for the first four air exchange rates analyzed. Fig. 3b is the same data as Fig. 3a plotted with the x-axis on a log-scale. The curves of these plots appear to be consistent with expectations given the first order decay model for the emissions factor. As the air exchange rate increases though the curve becomes much more linear. In addition, the maximum concentration and duration of the flush-out procedure are greatly reduced as air exchange rates increase. Fig. 5 is a line plot of the indoor air formaldehyde concentrations over time for the first four air exchange rates analyzed with particle board as the source of emissions.

Table 1: Maximum Allowable MDF Source Emitting Area for each air exchange rate and CDPH model quantities

	Source Area, m²		
Air Exchange Rate, h⁻¹	Residence	School	Office
0.5	0.35	0.35	0.33
1	0.25	0.25	0.25

2	0.30	0.30	0.30
3	0.38	0.38	0.39
4	0.46	0.46	0.48
5	0.54	0.54	0.57
6	0.63	0.63	0.67
7	0.72	0.72	0.75
8	0.81	0.81	0.85
10	0.99	0.99	1.03
12	1.15	1.15	1.23
14	1.35	1.35	1.40
16	1.51	1.51	1.60
CDPH quantity per	0.4235	0.3027	0.1695
m² of floor	m² doors	# desks	m² millwork

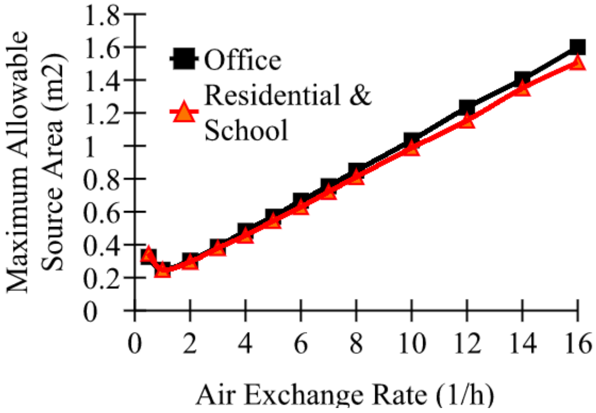

Fig. 2a: Maximum MDF area versus air exchange rate.

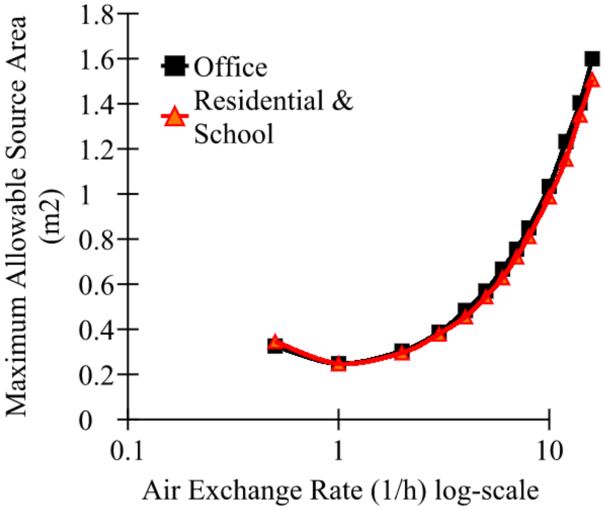

Fig. 2b: Log-scale version of data from Fig. 2a

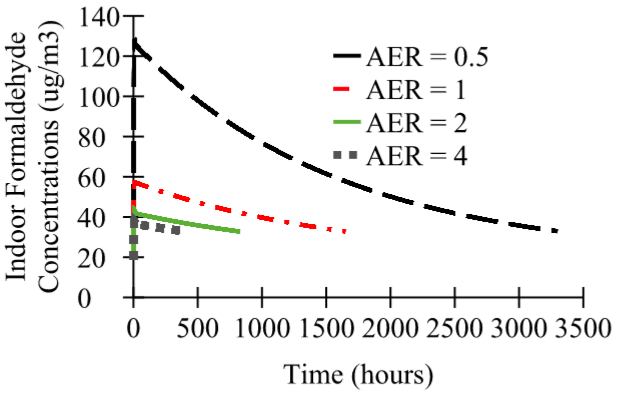

Fig. 3a: Indoor HCHO concentrations from MDF for the office and school cases where V=2.59 m³

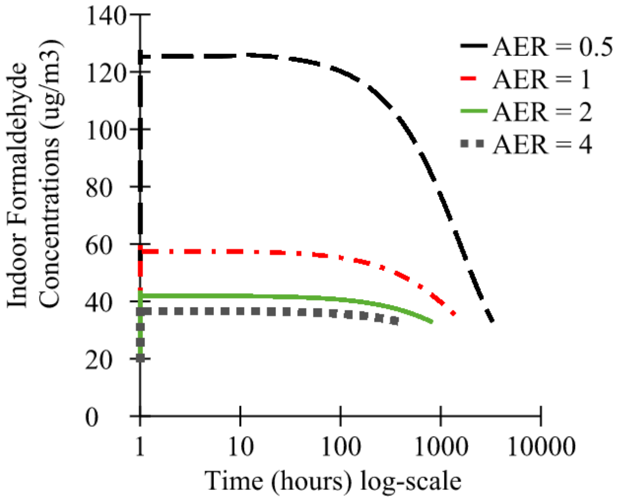

Fig. 3b: Log-scale version of data from Fig. 3a

3.2 Model Scenario Quantities

Table 1 also includes per m² of floor area estimates of PB or MDF sources that would be present in each scenario. These are derived from the CDPH typical quantities listed in each model scenario. These values which were listed in the CDPH method as whole room or whole house quantities have been divided by the scenario floor areas to try to normalize the data for easier comparison and evaluation.

If a student desk with chair can be assumed to have approximately 0.3 m² of exposed PB or MDF (AIA 2007) then 0.3027 desks x 0.3 m² = 0.091 m² and thus for the office and school scenario the low expectation of PB and MDF in the space means that formaldehyde emissions for PB and MDF are not an issue in meeting the maximum permissible concentration and in fact all air exchange rates allow for higher areas of PB and MDF to be used in those two scenarios. This is not the case for the residential scenario where air exchange rates of less than 4/h will produce maximum permissible areas for PB and MDF that are below the expected areas due to a large number of engineered wood products used in residential doors and cabinetry.

When comparing the allowable areas for PB and indoor air concentrations of formaldehyde as a result of PB emissions the short-term concentrations are much higher than those when modeling MDF. The emissions factor decays more rapidly for PB and thus allowable sources areas were larger for PB (compared to MDF) for low air exchange rates and allowable source areas were smaller for PB for higher air exchange rates where the point of inflection appears to occur at approximately 8 air changes per hour.

CONCLUSION

This project sought to determine the effectiveness of flush-out procedures using the LEEDv4 requirements. Using high air exchange rates of 4 per hour or more appear to generally succeed in bring the air pollutant level below the recommended limit by the end of the flush-out duration. Since this study only focused on particle board and MDF other sources such as paint, adhesives and sealants could contribute to the overall source emissions of HCHO and alter the allowable source areas. Using a first order decay rate emission model appears to show that low air exchange rates (below 4/h) which are typical for residential construction could significantly reduce the allowable source material areas. This might be of particular concern since it is in the residential scenario that there is a larger expectation of engineered wood products that could emit HCHO that are exposed in the form of millwork, cabinetry and doors when compared with school and office scenarios.

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