The IAQ and Energy Impacts of Reducing Formaldehyde Emissions in Commercial Buildings

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ABSTRACT

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to provide thermally comfortable conditions and to maintain acceptable indoor air quality (IAQ). At the same time, the operating costs of HVAC systems are often a large percentage of the total energy consumption of buildings, which constitutes 40 % of the primary energy consumed in the U.S. As efforts are pursued to reduce building energy use, some of which may include reductions in outdoor air ventilation rates, it is even more important to consider the impacts of these measures on IAQ. While IAQ involves many different contaminants and sources, formaldehyde is of particular importance given the wide use urea formaldehyde resins in the production of composite wood products, including components of furniture. Also, based on the health effects of exposure to formaldehyde, California has regulations on emissions from composite wood products, and federal regulations are expected in 2013. To better understand the IAQ and energy trade-offs of various approaches to reducing indoor formaldehyde concentrations, a series of simulations was performed using the multizone airflow model, CONTAM, in two low-energy commercial reference buildings developed by the U.S. Department of Energy. Annual airflow and contaminant simulations were performed using assumed emission rates of formaldehyde in these buildings. The impact of low-emitting materials and changes in ventilation rates on formaldehyde concentrations and energy use were evaluated to investigate how both low-energy and IAQ goals can be met.

INTRODUCTION

Building owners, designers and operators are challenged to reduce the environmental impacts of buildings, including energy consumption and associated greenhouse gas emissions, while maintaining indoor environments that are conducive to occupant health, safety, and productivity. Nevertheless, many discussions of sustainable, high-performance, as well as net-zero energy buildings, tend to focus on energy consumption. While energy is critically important, it is only one aspect of building performance and should not be pursued to the neglect of IAQ and other factors that affect the indoor environment (Persily and Emmerich 2012). When considering IAQ in the context of energy efficiency, one key design strategy is to reduce indoor contaminant sources. Source control, through the careful selection of indoor materials and furnishings, is a fundamental strategy for good IAQ (ASHRAE 2010b). Source control also offers the potential to reduce outdoor air ventilation rates, which can save energy for space conditioning. Such reductions are allowed under the IAQ Procedure of ASHRAE Standard 62.1-2010 (ASHRAE 2010a). Application of the IAQ Procedure presents several challenges, including the identification of the contaminants of concern for use in design, the adequacy of contaminant source data, and relevant concentration limits (Mendell and Apte 2010). However, reducing indoor sources can in theory allow the reduction of outdoor air ventilation rates.

Among the many contaminants of interest in terms of IAQ and the potential benefits of source control is formaldehyde (HCHO). Formaldehyde emissions have historically been associated with a wide range of building products and is of interest in terms of its impact on occupant health (OEHHA 2012). Any effort to control indoor contaminant sources with the goal of potentially reducing outdoor air ventilation rates, including implementation of the ASHRAE Standard 62.1 IAQ Procedure, generally should consider HCHO emissions.

The objective of this study is to simulate indoor HCHO concentrations as a means of investigating the trade-offs between source control, ventilation and energy use. In addition, it serves as a demonstration of the utility of multizone airflow and contaminant transport simulations in conjunction with energy modeling tools (Ng et al. 2013b). Historically, ventilation and energy analyses have been performed in isolation, with energy simulations treating ventilation rates as an input without considering its variation due to weather effects and the physical coupling between air and energy flows. IAQ impacts are rarely analyzed during design and more rarely linked to energy analysis. However, addressing the challenges of designing, building and operating low energy buildings with good IAQ requires more complete design and analysis approaches that integrate airflow, IAQ and energy simulations. In this study, indoor HCHO concentrations are simulated in two commercial buildings using the CONTAM simulation model (Walton and Dols 2013) with both typical and reduced HCHO emission rates as inputs. The simulations also include cases with reduced outdoor air ventilation rates with the lower HCHO emission rate and increased ventilation with the higher HCHO emission rate. The indoor HCHO concentrations for these cases are examined, along with indoor carbon dioxide (CO_2) concentrations as an indicator of contaminants associated with occupancy, and the levels of energy use at the different ventilation rates.

METHODS

Building models

To demonstrate the effects of HCHO emissions and ventilation on IAQ and energy, two commercial buildings were selected from the available DOE reference buildings (DOE 2011), the Medium Office and Stand Alone Retail. The Medium Office is a three-story, 4982 m^2 building with a return air plenum above each floor. The Stand Alone Retail is a one-story, 2294 m^2 building. The buildings were simulated in both CONTAM, a multizone airflow and contaminant transport modeling program (Walton and Dols 2013), and EnergyPlus, a building energy simulation program (DOE 2012). The ventilation rates in the DOE reference buildings were selected to comply with the ventilation requirements in ASHRAE 62-1999 (ASHRAE 1999), and the same ventilation rates were used in the CONTAM models as those in the DOE models. For detailed descriptions of the buildings, see Ng et al. (2012) and Ng et al. (2013a).

Contaminants

Two indoor contaminants were modeled in the Medium Office and Stand Alone Retail, HCHO from building materials and furnishings and occupant-generated CO_2. The outdoor concentration of HCHO was assumed to be 4 $\mu g/m^3$ (EPA 2006) and that of CO_2 was assumed to be 732 mg/m^3. Constant outdoor concentrations of HCHO and CO_2 were used for the purposes of modeling, though in reality outdoor contaminant concentrations will vary in time and space. Two values for the indoor whole-building HCHO emission factor were used: 50 $\mu g/h{\bullet}m^2$ and 5 $\mu g/h{\bullet}m^2$, referred to respectively as the "typical" and "low" emission factor in this study, based on the range of factors reported in two large field studies (Bennett et al. 2011; Hodgson et al. 2003). The assumed generation rate of CO_2 was 0.3 L/min•person (ASHRAE 2010a). While the use of a single value ignores variations in CO_2 generation among different indivduals, it is adequate for the relative comparisons between different modeling cases presented in this paper. HCHO and CO_2 sources were defined for all occupied zones. The only unoccupied zones in the Medium Office were the restrooms, stairwells, elevator shafts, and plenums. The only unoccupied zone in the Stand Alone Retail was the restroom.

Simulations

Four CONTAM and three EnergyPlus simulations were performed for each of the two buildings as follows:

- CONTAM: Typical HCHO emission factor, ASHRAE 62 ventilation rates
- CONTAM: Low HCHO emission factor, ASHRAE 62 ventilation rates
- CONTAM: Typical HCHO emission factor, Doubling of the ASHRAE 62 ventilation rates
- CONTAM: Low HCHO emission factor, Halving of the ASHRAE 62 ventilation rates
- EnergyPlus: ASHRAE 62 ventilation rates
- EnergyPlus: Double the ASHRAE 62 ventilation rates
- EnergyPlus: Half of the ASHRAE 62 ventilation rates

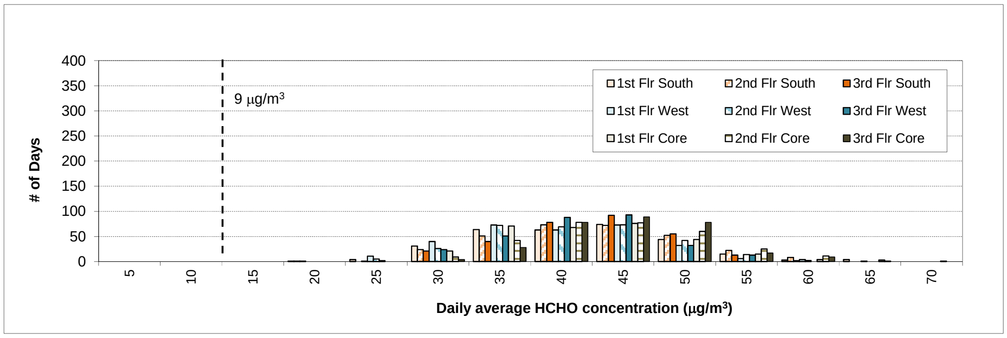
Annual simulations were performed in both CONTAM and EnergyPlus using weather data for Chicago since there are a relatively high percentage of buildings in the U.S. in this climate zone (Deru et al. 2011). Also, Chicago weather covers a wide range of outdoor temperatures and wind speeds.

RESULTS

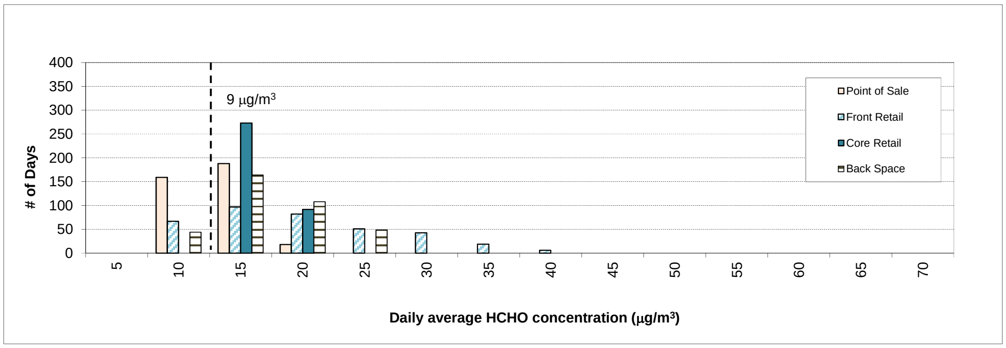
The daily average HCHO concentrations in occupied zones of the Medium Office and Stand Alone Retail for the typical HCHO emission factor (50 μg/h•m^2) and the Standard 62 ventilation rates **are shown in Figure 1**. These averages cover the hours of 6 a.m. to 10 p.m, when the HVAC system is on. Along the *x*-axis are "bins" of HCHO concentration. For example, the first bin marked with a 5 includes concentrations below 5 μg/m^3, and the bin marked 10 includes concentrations between 5.01 μg/m^3 and 10 μg/m^3. The *y*-axis is the number of days in a year for which the daily average HCHO concentration fell within a particular bin. For instance, **in Figure 1**, there were about 50 days to 100 days for which the daily average concentration in each zone in the Medium Office fell between 35 μg/m^3 and 50 μg/m^3. The vertical dashed line at 9 μg/m^3 refers to the California Office of Environmental Health Hazard Assessment (OEHHA) 8-hour exposure guideline (OEHHA 2012). Note that other guideline concentrations exists, such as 100 μg/m^3 for a 30 minute exposure issued by the World Health Organization (WHO 2010) and NIOSH limits of 20 μg/m^3 as a time-weighted average over a 40-hour work week and 123 μg/m^3 for a 15 minute exposure (NIOSH 2010). It is noted that since the HCHO concentrations are grouped into bins, a concentration below the OEHAA guideline is plotted in the bin marked 10 even if the concentration is at or below 9 μg/m^3.

The building average HCHO concentrations calculated for occupied zones in the Medium Office (25th and 75th percentiles **in Table 1** are respectively 35 μg/m^3 and 44 μg/m^3) are above the means measured in Hodgson et al. (2003) (14.8 μg/m^3) and the EPA BASE study (EPA 2006) (16 μg/m^3). In contrast, the building average HCHO concentrations for occupied zones in the Stand Alone Retail (25th and 75th percentiles **in Table** 1 are respectively 11 μg/m^3 and 17 μg/m^3) are similar to the means measured in Bennett et al. (2011) (23 μg/m^3). For the Medium Office, the average concentrations are about four to fives times higher than OEHHA guideline. For the Stand Alone Retail, the modeled values are no more than twice the OEHHA guideline. Nevertheless, for the purposes of this study, rather than the absolute HCHO concentrations, it is the relative concentrations between the different simulated cases that are of most interest. **Table 1** also shows the 25th, median, and 75th percentiles of the daily peak CO_2 concentrations in the occupied zones of the Medium Office and Stand Alone Retail. The daily peak CO_2 concentrations for these two buildings simulated with Standard 62 ventilation rates are below 1800 mg/m^3 **as shown in Table 1**, which is a common benchmark for indoor CO_2 concentrations though it is not a guideline value based on health concerns (Persily 1997).

For the typical HCHO emission rate and twice the Standard 62 ventilation rates, the 25th and 75th percentiles of daily average HCHO concentrations in the Medium Office are respectively 20 μg/m^3 and 24 μg/m^3, which are about 50 % reductions from the concentrations for the Standard 62 ventilation rates **as shown in Figure 2a and Table 1**. For the



(a) Medium Office, typical HCHO emissions, Standard 62 ventilation rate



(b) Stand Alone Retail, typical HCHO emissions, Standard 62 ventilation rate

Figure 1 Distribution of daily average HCHO concentrations for a year for (a) Medium Office and (b) Stand Alone Retail when simulated with typical HCHO emission factor and Standard 62 ventilation rates

Table 1. Summary of daily peak and average indoor concentrations and annual energy use

	Daily peak CO_2 concentration (mg/m³)			Daily average HCHO concentration (µg/m³), typical emission			Daily average HCHO concentration (µg/m³), low emission			Annual total building energy use (GJ)
	25th PCTL	Median	75th PCTL	25th PCTL	Median	75th PCTL	25th PCTL	Median	75th PCTL	
Medium Office										
Std 62 rates	1205	1295	1341	35	40	44	7.1	7.6	8.0	2952
Double Std 62 rates	1012	1043	1056	20	22	24	NA	NA	NA	3273
Half Std 62 rates	1327	1477	1556	NA	NA	NA	8.1	8.9	9.6	2782
Stand Alone Retail										
Std 62 rates	1126	1284	1469	11	13	17	4.7	4.8	5.0	2158
Double Std 62 rates	1030	1142	1257	9	11	13	NA	NA	NA	3113
Half Std 62 rates	1243	1463	1787	NA	NA	NA	4.9	5.3	5.9	1704

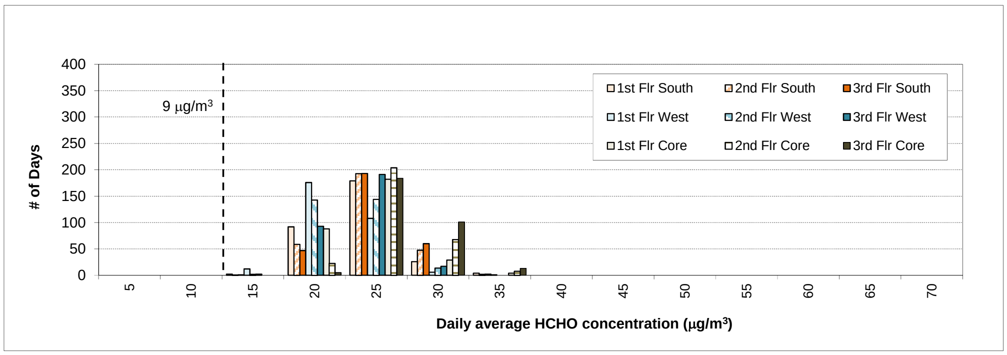
* Note: daily peak CO_2 concentrations are shown for the peaks among the individual occupied zones in each building.

Stand Alone Retail, doubling the ventilation rates results in 25th and 75th percentile HCHO concentrations of 9 µg/m³ and 13 µg/m³, which are about 20 % to 25 % reductions from the concentrations for the Standard 62 ventilation rates **as shown in Figure 2b and Table 1**. It is noted that the shift in the distribution of HCHO concentrations observed **in**

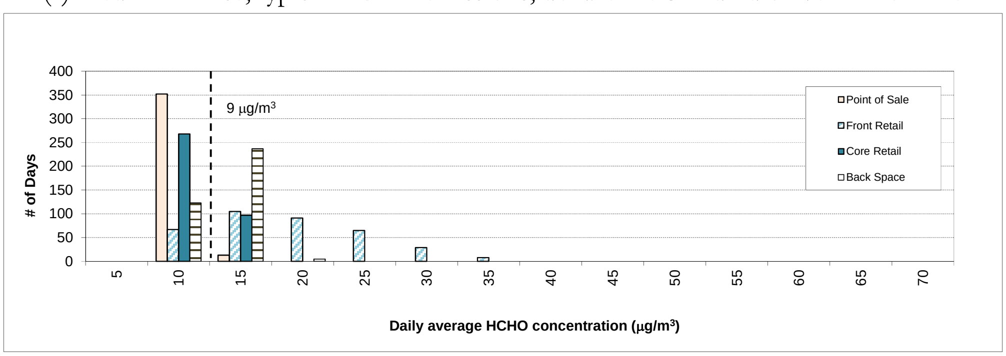
Figure 1 and Figure 2 is not proportional with a change in ventilation rates. The change in ventilation rates affects how much higher the indoor concentration is relative to outdoors and therefore the change in the indoor concentration is not linear with the ventilation rate.

Doubling the ventilation rates reduces the daily peak CO_2 concentrations in both buildings as expected, which were already below 1800 mg/m^3 **as shown in Table 1**. The energy impact of doubling the ventilation rate in the Medium Office is a 10 % increase in total building energy use and a 40 % increase for the Stand Alone Retail **as shown in Table 1**.

When the HCHO emission factor is decreased by an order of magnitude to 5 µg/h•m^2, with no change in ventilation rates, the daily average HCHO concentrations in the Medium Office and Stand Alone Retail decrease by two to four times their concentrations with the typical emission factor. In both the Medium Office and Stand Alone Retail, the average HCHO concentrations are below the 10 µg/m^3 **as shown in Figure 3a** and **Figure 4a** (note that the OEHHA guideline of 9 µg/m^3 falls within the 5 µg/m^3 to 10 µg/m^3 range) **and Table 1**. Thus, for buildings with typical or high HCHO emission rates, reducing emissions is clearly a key strategy for reducing HCHO concentrations.



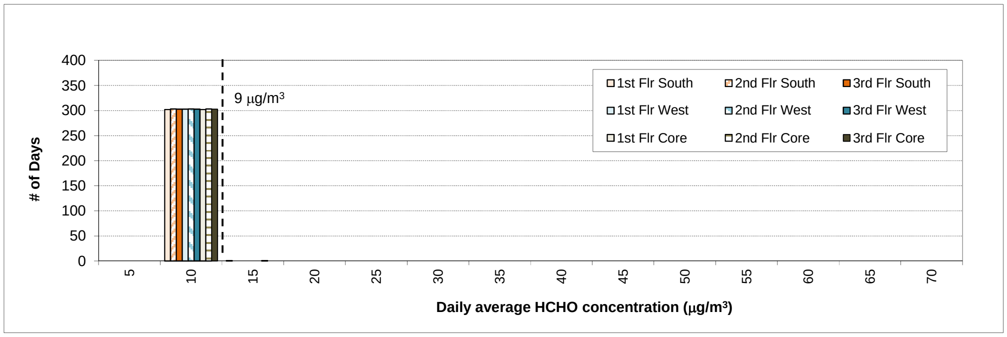
(a) Medium Office, typical HCHO emissions, double the Standard 62 ventilation rate



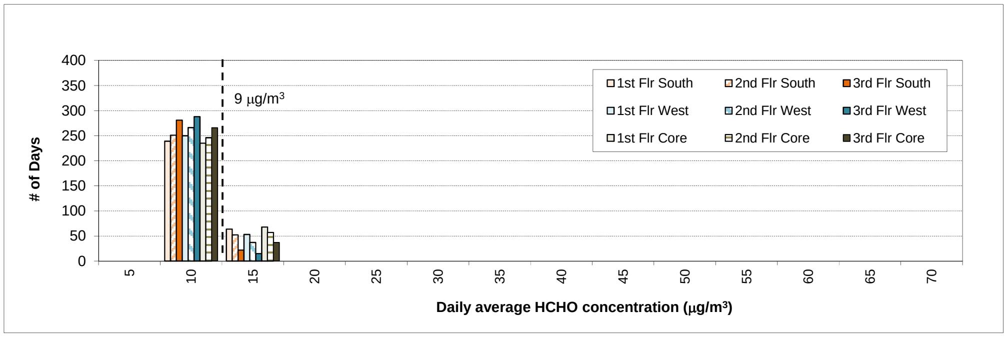
(b) Stand Alone Retail, typical HCHO emissions, double the Standard 62 ventilation rate

Figure 2 Distribution of daily average HCHO concentrations for a year for (a) Medium Office and (b) Stand Alone Retail when simulated with typical HCHO emission factor and double Standard 62 ventilation rates

For the low HCHO emission rate and one-half the Standard 62 ventilation rate, the HCHO concentrations increase by about 20 % **as shown in Figure 3b and Table 1** when compared to the same source condition and the Standard ventilation rate. For the Stand Alone Retail, the HCHO concentrations remained below 10 µg/m^3 when one-half the Standard 62 ventilation rate was applied, **as shown in Figure 4b and Table 1**. The reduction in ventilation rates results in an increase in CO_2 concentrations, but the concentrations do not exceed 1800 mg/m^3 in the Medium Office and only do so in the Stand Alone Retail for a few hours out of the year **as shown in Table 1**. The reduction in ventilation rate results in a 6 % reduction in energy use for the Medium Office, and an 11 % reduction in energy use for the Stand Alone Retail **as shown in Table 1**. Therefore, reducing the ventilation rate in the Stand Alone Retail where HCHO concentrations are low may be acceptable from an IAQ perspective and also will result in substantial energy savings.

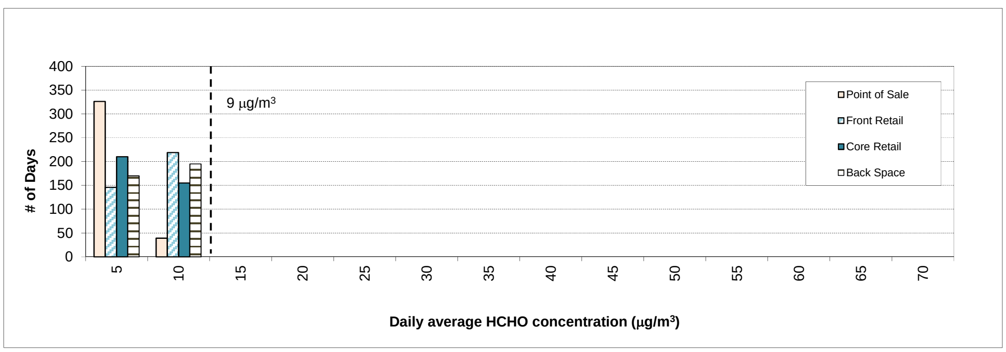


(a) Medium Office, low HCHO emissions, Standard 62 ventilation rate

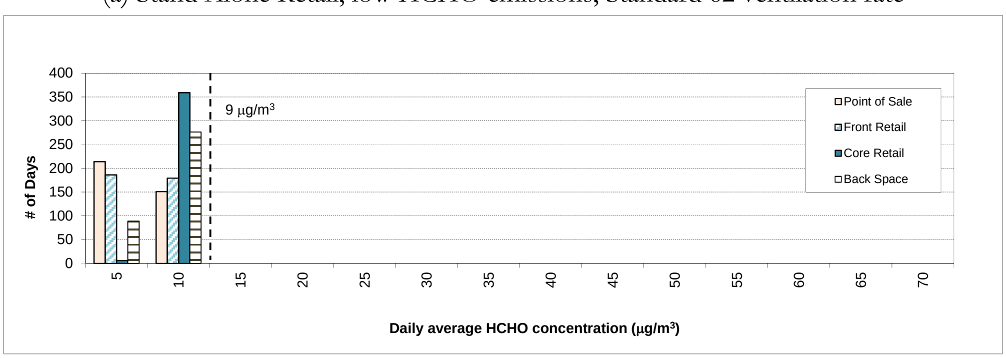


(b) Medium Office, low HCHO emissions, half of the Standard 62 ventilation rate

Figure 3 Distribution of daily average HCHO concentrations for a year for Medium Office when simulated with low HCHO emission factor and (a) Standard 62 and (b) half of the Standard 62 ventilation rates



(a) Stand Alone Retail, low HCHO emissions, Standard 62 ventilation rate



(b) Stand Alone Retail, low HCHO emissions, half of the Standard 62 ventilation rate

Figure 4 Distribution of daily average HCHO concentrations for a year for Stand Alone Retail when simulated with low HCHO emission factor and (a) Standard 62 and (b) half of the Standard 62 ventilation rates

DISCUSSION

The reduction of design ventilation rates allowed as a result of contaminant source control is a potential strategy to improve IAQ and save energy. While progress is being made to implement such design approaches, more work is needed in several areas, including understanding contaminant sources and emission rates and establishing indoor contaminant benchmarks for HCHO and other airborne contaminants. Air filtration and air cleaning also may play important roles. A key step in making progress toward building and ventilation system design based on indoor contaminant levels is the integration of airflow, IAQ and energy simulation tools, so the trade-offs between different design decisions can be better understood during the building design process.

This study demonstrated the impact of reducing HCHO emissions on HCHO concentrations and ventilation rates. In some buildings, HCHO concentrations may be reduced to below the OEHHA guideline, for example, while allowing for the potential of saving energy by reducing ventilation rates. Nevertheless, reducing ventilation rates based on HCHO emissions alone is not necessarily acceptable given the range of other indoor contaminants in buildings, many of which do not have guidelines for occupant exposures. Further, in buildings such as retail, it may not be feasible to control the emissions from sources other than building materials, such as inventory. In the retail building, doubling the ventilation rate was not shown to be an appropriate solution to reducing HCHO concentrations as the energy penalty was 10 % to 40 % and did not result in as great of a reduction in HCHO concentration as reducing the HCHO emissions.

To further understand the impact of reducing HCHO emissions on building materials and furnishings, additional research needs to examine the impact of ventilation strategies on indoor concentrations of other contaminants, as well as the impact on energy. Other building types with different HCHO emission rates and different contaminant sources should also be analyzed to determine under what circumstances reducing emissions, and reducing or increasing ventilation rates, are effective for ensuring occupant health and saving energy. There is also a need for field measurements of VOC emissions, including HCHO, in buildings, especially those that claim to use low VOC-emitting or formaldehyde-free materials. Such field testing would also be very helpful if it included measurements under different ventilation strategies with various source control measures.

CONCLUSION

The conditioning of air in buildings constitutes 40 % of the primary energy consumed in the U.S. Thus, the design and operation of these systems is often a primary target for implementing energy-saving strategies. Nevertheless, when considering strategies such as reducing ventilation rates, it is important to understand the IAQ impacts. In this study, the concentrations of indoor HCHO and CO_2 were simulated under three different ventilation rates – ASHRAE Standard 62 ventilation rates, double these rates, and half these rates. When a typical HCHO emission factor was simulated with the Standard 62 ventilation rates, the HCHO concentrations were two to five times higher than the OEHHA 8-hour exposure guideline. When the ventilation rates were two times the Standard 62 rates with the same HCHO emissions, the HCHO concentrations were reduced 20 % to 50 %. In the Medium Office and Stand Alone Retail, simulations with the Standard 62 rates resulted in acceptable indoor HCHO concentrations per the OEHHA guideline, when the HCHO emission factor was low (four-fold decrease), without resulting in high CO_2 concentrations. It may be possible to save energy in buildings with low HCHO emissions by reducing ventilation rates without HCHO exceeding the OEHHA guideline, as demonstrated in the Stand Alone Retail but not in the Medium Office. However, such a reduction would require consideration of indoor and outdoor contaminants beyond HCHO. Nevertheless, controlling or reducing HCHO emissions is an effective strategy for reducing HCHO concentrations, and may also be part of broader strategies to save energy through reduced ventilation rates.

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