Building and Environment 58 (2012) 179–187

Contents lists available at SciVerse ScienceDirect

Building and Environment

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

Indoor air quality analyses of commercial reference buildings

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ARTICLE INFO

Article history:
Received 7 June 2012
Received in revised form
18 July 2012
Accepted 21 July 2012

Keywords:
Indoor air quality
CONTAM
Reference buildings
Simulation

ABSTRACT

Sixteen commercial reference buildings were created in the multizone airflow and contaminant transport program CONTAM in order to support airflow and indoor air quality (IAQ) analyses, which are not possible using the existing EnergyPlus input files for these buildings. Annual airflow and contaminant simulations were performed in CONTAM for six of the buildings. Contaminant analyses were performed for occupant-generated carbon dioxide (CO_2), volatile organic compounds (VOC) from indoor sources, outdoor particulate matter, and outdoor ozone. In all of the selected buildings and zones, the simulated indoor ozone and PM 2.5 concentrations did not exceed indoor limits set by the World Health Organization. For CO_2 and VOC, for which no similarly relevant indoor concentration standards or limits exist, the simulated concentrations were within expected ranges based on published field measurements in commercial buildings. The results of this study provide a baseline for subsequent use of these models to investigate approaches to building ventilation and other technologies that are intended to simultaneously reduce building energy consumption while maintaining or improving indoor air quality.

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1. Introduction

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to provide thermally comfortable conditions and to maintain acceptable indoor air quality (IAQ). Sixteen commercial reference buildings, previously defined by the National Renewable Energy Laboratory, were entered into the multizone airflow and contaminant transport program CONTAM in order to support IAQ analyses of these buildings and future evaluations of the IAQ impacts of building design and operation. The 16 reference buildings characterize more than 60% of the commercial building stock in the U.S. [1]. These reference buildings include 15 commercial buildings and one multi-family residential building. There are three versions (or vintages) of each reference building: new, post-1980, and pre-1980 construction. The three vintages differ in insulation values, infiltration rates, lighting levels, and HVAC system types. The new construction models were developed to comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 [2], the post-1980 models to comply with the minimum requirements of ASHRAE/IES Standard 90.1-1989 [3], and the pre-1980 models to comply with requirements from previous standards and studies of construction practices.

The reference buildings were created to assess new technologies and support the development of energy codes and standards, and therefore their definitions are focused on capturing energy performance, not IAQ. Many discussions of building energy efficiency neglect potential impacts on IAQ or view acceptable IAQ as being in conflict with energy efficiency [4]. However, saving energy at the expense of IAQ has the potential to negatively impact the health, comfort, and productivity of building occupants. Therefore, there is a need to evaluate the IAQ impacts of energy efficiency measures as well as a need for improved modeling capabilities to assess a range of IAQ issues in buildings.

Multizone airflow and contaminant transport models exist and have been used to examine the IAQ impacts of energy efficiency technologies. Persily et al. [5] used CONTAM to show that the use of DCV resulted in 10%–80% energy savings without necessarily compromising certain aspects of IAQ. Carpenter [6] used an airflow-thermal model to show that the use of DCV resulted in 20%–30% energy savings, reduced CO_2 levels, and 50%–100% reduction in formaldehyde concentrations.

The studies above demonstrate the application of multizone airflow and IAQ analyses in evaluating energy efficiency technologies and other issues. To support airflow and IAQ analyses of the reference buildings, models of the 16 buildings were created (including new, post-1980, and pre-1980 versions) in CONTAM (version 3.0). The availability of the CONTAM models will support the study of technologies and approaches that can simultaneously reduce building energy consumption while maintaining or

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0360-1323/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.buildenv.2012.07.008

improving IAQ as well as future studies of a range of commercial building IAQ issues. This paper gives a description of the CONTAM building models and the contaminant simulations performed. The contaminant results are then compared to relevant IAQ guidelines and published field measurements.

2. Building descriptions

This section provides a brief description of the reference buildings; detailed descriptions are available in Deru et al. [1] and Ng et al. [7]. In this paper, contaminant simulations were performed for six of the sixteen reference buildings, representing each type of occupancy covered by the commercial reference buildings. The buildings simulated were: Full Service Restaurant, Hospital, Medium Office, Primary School, Small Hotel, and Stand-Alone Retail. Table 1 lists the six simulated reference buildings and their floor area, number of floors, and number of zones in the CONTAM models. The CONTAM models employ the occupancy and outdoor air ventilation requirements that were defined in the EnergyPlus input files. Details on occupancy schedules and ventilation requirements are found in Ng et al. [7]. In general, the buildings are occupied when the HVAC system is scheduled to be on. Except for the Primary School and Small Hotel, the occupancy in the other buildings is similar among all the zones except for the peak number of occupants. For instance, though the Full Service Restaurant the Kitchen and Dining zones are occupied at the same time, the Dining zone has about 40 times more peak occupants. In contrast, the Primary School has zones with relatively low occupancy for most of the operating day (classrooms), but high occupancy in other zones for a short period of the day (Cafeteria). The differences in occupancy are shown to have an effect on peak and average contaminant concentrations.

3. Modeling approach

CONTAM simulations were performed for the "new" vintages of the reference buildings listed in Table 1 using typical meteorological year, version 2 (TMY2) weather data for Chicago, IL [8]. Building exterior envelope leakage was modeled using an effective leakage area (A_L) of 5.27 cm^2/m^2 at a reference pressure difference (ΔP_r) of 4 Pa, a discharge coefficient (C_D) of 1.0, and a pressure exponent (n) of 0.65 for all three vintages of the reference buildings. The effective leakage area of partitions between floors and between zones used the same value as the exterior wall leakage. The connections between zones that would not have a physical partition, such as within an open office or retail space, were modeled as large openings with discharge coefficient $C_D = 0.6$ and $n = 0.5$. Transfer grilles and door undercuts were modeled between restrooms and adjacent zones. Wind effects were calculated using a wind pressure profile calculated using wind pressure coefficient (C_P) relationships found in Swami and Chandra [9]. A wind speed modifier of 0.36, which corresponds to "suburban" terrain [10], was applied to all exterior leakage paths. This parameter is used in CONTAM to account for the effects of local terrain on the variation of wind speed with height above ground level. For openings on roofs, C_P was −0.5 for all wind directions [11].

The minimum amount of outdoor ventilation air for each zone (or HVAC system) was specified in the EnergyPlus models using ASHRAE 62.1-1999 for all vintages [12], and these values were included in the CONTAM models. Note that the minimum ventilation requirements in the different building vintages may be expected to vary based on the version of ASHRAE 62.1 required by relevant building code at the time. The common design goal of pressurizing commercial buildings was accounted for in the CONTAM models by returning 90% of the supply airflow rate to the HVAC system. When the outdoor air quantity to a zone was less than 10% of the supply, the return airflow rate was equal to the supply minus the outdoor airflow rate. For buildings with large exhaust fans, i.e., the two restaurants, the total outdoor air intake was approximately equal to the total exhaust. Details on the supply, return, and outdoor ventilation rates in the CONTAM models can be found in Ng et al. [7].

Contaminant simulations were performed for four contaminants: carbon dioxide (CO_2), ozone, particulates less than 2.5 μm in diameter (PM 2.5), and a generic volatile organic compound (VOC). The VOC is not intended to represent any specific compound or compounds, but rather to represent a generic indoor source associated with materials and occupant activities. PM 2.5 is simulated using a diameter of 0.3 μm, which impacts the deposition rates and filtration efficiency. Outdoor concentrations of ozone and PM 2.5 were downloaded from the U.S. Environmental Protection Agency (EPA) Air Quality Standard (AQS) database [13].

Table 2 lists the minimum, maximum, mean, and standard deviation of the outdoor concentration of ozone and PM 2.5 for Chicago, IL. Based on the 2010 ozone data from the EPA database for Chicago, there were only 4 h during the year for which the outdoor ozone level exceeded the National Ambient Air Quality Standards (NAAQS) limit of 150 μg/m^3 averaged over 8 h [14]. Based on the 2010 PM 2.5 data, there were 868 h during the year for which the outdoor PM 2.5 level exceeded the NAAQS limit of 35 μg/m^3 averaged over 24 h [14]. The outdoor concentrations of CO_2 and VOC were assumed to be constant at 648 mg/m^3 and zero respectively.

Indoor contaminant sources included occupant-generated CO_2 and VOCs from materials and occupant activities. A CO_2 source was defined in all occupied zones, with an assumed generation rate of 0.3 L/min per person [15]. The CO_2 source strengths in the CONTAM models varied with occupancy based on schedules in the EnergyPlus models. Detailed occupancy schedules for each building are found in Ng et al. [7]. An area-based VOC source was defined in all occupied building zones. In occupied zones, a 0.5 mg/m^2•h source was included during system-on hours and reduced by 50% during system-off hours [5]. Note that this VOC source strength is not intended to characterize emissions in any specific building but rather to serve as a reasonable value for the purposes of these simulations, providing the ability to compare predicted VOC levels for different cases of building configuration and ventilation system design and operation. Nevertheless, the assumed source strength is consistent with experimental studies in an office building where

Table 1
Summary of reference buildings.

Building	Floor area (m^2)	No. of floors	No. of CONTAM zones
Full Service Restaurant	511	1	3
Hospital	22,422	6	64
Small Hotel	4013	4	67
Medium Office	4982	3	23
Primary School	6871	1	25
Stand-Alone Retail	2294	1	6

Table 2
Summary of outdoor contaminant concentrations for Chicago.

Outdoor contaminant	Daily average contaminant concentrations (μg/m^3)				Daily peak contaminant concentrations (μg/m^3)			
	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
Ozone	47	6	106	21	80	12	155	29
PM 2.5	18	1	57	10	30	4	94	14