Building and Environment 100 (2016) 186–196

Contents lists available at ScienceDirect

Building and Environment

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

Impact of ventilation and filtration strategies on energy consumption and exposures in retail stores

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ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form
26 January 2016
Accepted 28 January 2016
Available online 1 February 2016

Keywords:
Dilution
Filtration
HVAC energy use
Contaminants of concern
Commercial buildings
ASHRAE Standard 62.1

ABSTRACT

Different ventilation strategies can have an enormous impact on both exposures to contaminants of concern (COCs) and energy use in retail buildings. We applied a multi-contaminant model of an area-normalized retail store, and developed estimates for distributions of model inputs. We then used these distributions in a Monte Carlo simulation for six cities to compare the impacts of the ASHRAE 62.1–2013 ventilation rate procedure (VRP), demand controlled ventilation (DCV), and indoor air quality procedure (IAQP), with or without using a high particulate efficiency filter. Results showed that for cities where outdoor $PM_{2.5}$ concentration is low, adopting the IAQP with low efficiency $PM_{2.5}$ filter in grocery stores and the VRP with high $PM_{2.5}$ efficiency in non-grocery stores yielded the greatest exposure benefits. For cities with high outdoor $PM_{2.5}$ concentration, adopting the VRP with high $PM_{2.5}$ efficiency for all store types yielded the greatest exposure benefits. However, these exposure benefits also caused an increase in energy consumption, and the magnitude depends on the city's climate, outdoor $PM_{2.5}$ concentration and the retail store type. We propose a new pollutant exposure control ventilation (PECV) strategy, where ventilation rates are weighed against exposure to different COCs, and the ventilation rate that is most climatically advantageous is chosen.

1. Introduction and background

The indoor air quality (IAQ) of retail buildings is an important occupational exposure consideration: the retail sector employs 15 million workers, approximately 10% of the U.S. workforce [1], and the average American above the age of fifteen spends 0.48 h per day purchasing goods and groceries [2]. Inside these buildings, ventilation is mainly used to promote the comfort of occupants by diluting emissions of indoor-generated pollutants. The measurable benefits of increased ventilation rates are decreased sick building syndrome symptoms and improved perceived air quality, leading to economic benefits including better productivity and positive impact on retail sales [3–6]. However, in certain situations ventilation may have a negative impact on indoor air quality as it can transport ambient pollution indoors (e.g., [7]). Beside its impact on air quality, ventilation has a great impact on overall building energy consumption; just considering the retail sector, eliminating ventilation would decrease the total energy use index (i.e., building's energy use as a function of its size) by 8.4% on average, with the gas energy use index decreasing by 27.8% [8]. Balancing air quality concerns and energy usage in retail buildings is key to reducing energy consumption without increasing exposure of the occupants.

Over the past two decades, researchers and practitioners have expended considerable effort to find the minimum ventilation rates that will reduce energy consumption while maintaining an acceptable indoor air quality. Among the most commonly adopted ventilation rates are those specified by ASHRAE Standard 62.1–2013 [9]. This standard provides two alternative procedures for selecting the minimum ventilation rate for commercial buildings: 1) a prescriptive approach: the ventilation rate procedure (VRP); and 2) a performance-based approach: the indoor air quality procedure (IAQP).

1.1. Ventilation rate procedure (VRP)

The VRP is the more widely used procedure. The prescribed minimum ventilation rates are the sum of two quantities: the

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http://dx.doi.org/10.1016/j.buildenv.2016.01.026
0360-1323/

minimum rate of outdoor air supply per unit floor area, and the minimum rate of outdoor air supply per occupant. The VRP is assumed to maintain an acceptable indoor air quality as perceived by at least 80% of occupants. Bluyssen et al. [10] tested 44 buildings with mean ventilation rates of 25 L/s·person (far above the current ventilation rates specified by the VRP) and found that air quality in 64% of these buildings did not satisfy 80% of the occupants. In addition, a review of ventilation measurements in retail stores found that half of the stores tested met or exceeded the VRP; nonetheless, these ventilation rates were not sufficient to keep all pollutants below their most conservative limits [11]. Specifically, there is no documentation of the adequacy of VRP in maintaining an acceptable indoor air quality in retail buildings.

One variation to the VRP that further saves energy is the use of demand control ventilation (DCV), often based on CO_2 concentrations in buildings with variable occupancy. The impact of DCV on indoor air quality remains less investigated. To our knowledge, only eight literature studies investigated whether controlling ventilation by measuring occupancy (DCV-based CO_2) could keep pollutants (e.g., formaldehyde, TVOC, radon) below their reference or regulatory limits [12–20]. Five of these studies found that DCV was not sufficient to control the measured pollutants below their established limits. DCV-based CO_2 does not generally control outdoor-generated pollutants, nor does it account for pollutants generated indoors but independently of human activities. Thus, the ability of VRP or DCV to maintain an acceptable IAQ in buildings depends highly on the source strengths, pollutant sources, and infiltration rates, which are specific to building type and location.

1.2. Indoor air quality procedure (IAQP)

Another approach to control ventilation is to follow the performance-based approach, the IAQP, specified in ASHRAE Standard 62.1–2013 [9]. In the IAQP, contaminants of concern (COCs) are selected and the minimum ventilation rate is defined to be the larger rate resulting from an objective assessment based on COCs emission rates and concentration limits, and a subjective assessment of air quality. In the objective assessment, the IAQP requires designers to select the ventilation rate that will keep each individual COC below its established limit. This ignores the fact that some pollutants (e.g. ozone, and some particles) can be generated outdoors, and keeping the ventilation rate to a minimum may be more advantageous from both exposure and energy perspectives. Furthermore, there is often a lack of knowledge of source strengths (used in the IAQP to calculate the required ventilation rate) in different types of buildings and a poor understanding of how different sources of emissions should be added together.

The impacts of VRP, DCV-based CO_2, and IAQP on energy usage and exposure to contaminants of concern, whether generated indoors, outdoors or both, are not sufficiently investigated. This is especially the case for retail stores, which have very few studies on how ventilation rates affect energy, and health. The main objective of this paper is to determine an exposure-based, energy-efficient ventilation strategy for different retail types and locations.

Specifically this paper answers the following questions:

1. What are the effects of ventilation rates determined by VRP, DCV-based CO_2, and IAQP on COCs concentrations found in retail buildings?
2. What happens to COCs concentrations if we increase particle filter efficiency?
3. What is the optimal ventilation–filtration combination strategy that will lead to a balance between exposure to pollutants and energy consumption?

The results from this study could help building designers and other researchers in understanding the impact of different ventilation strategies recommended by energy standards on indoor air quality and HVAC energy use in retail buildings. Additionally, this paper proposes a new ventilation strategy suitable for different retail types and locations that reduces energy consumption without increasing indoor exposures.

2. Simulation methodology

2.1. Overview

The methodology comprises four steps: (1) identifying contaminants of concern; (2) assessing the impact of control strategies on COCs concentrations; (3) quantifying exposures; and (4) computing energy consumption. Each step is summarized below.

2.1.1. Contaminants of concern in retail buildings

Zaatari et al. [11] identified contaminants of concern in retail buildings by using data compilation from 28 literature studies (235 stores, > 70 pollutants), and found that $PM_{2.5}$ and acrolein are the main contaminants of concern for which control methods should be prioritized, with the caveat mentioned in the study that more acrolein concentration data is needed to confirm the finding about acrolein. In the present paper, we used these identified contaminants of concern as well as two additional pollutants, formaldehyde and acetaldehyde, because they were found above their reference exposure limit in few of the tested stores (e.g., Siegel et al., 2013). These two pollutants were used for further assurance that the selected control strategy will not increase concentrations of these pollutants above the level where they will be considered as contaminants of concern (COCs).

2.1.2. Impact of control strategies on COCs concentrations

We used a time-averaged mass balance multi-contaminant model to evaluate two alternative exposure control scenarios. The first control scenario calculates $PM_{2.5}$, acrolein, formaldehyde, and acetaldehyde concentrations based on different ventilation strategies. The second scenario complements the first scenario with increased $PM_{2.5}$ filtration.

Estimates for distributions of inputs across the retail sector were modeled by Monte Carlo simulations for multiple combinations of cities, seasons, store types, and period of day. Six US cities were chosen to cover different climates as well as different outdoor air quality: Austin, Philadelphia, Minneapolis, Seattle, Los Angeles, Phoenix; two seasons: winter and summer; two store types: grocery and non-grocery (reflective of different ventilation requirements in ASHRAE 62.1–2013 [9]); and two periods of the day: store-open and store-closed. A summary of the weather information related to the cities is provided in the supporting information.

The time-average pollutant mass-balance model, provided by Riley et al. [21] is modified by adding an indoor source emission term:

$$C_{out} \times (Q_{OA} \times (1-\eta) + p \times Q_i) + E \times V - C_{in} \times (Q_R \times \eta + \beta \times V + Q_{EX}) = 0 \quad (1)$$

C_{out} and C_{in} are the outdoor and indoor concentrations [μg/m^3], Q_{OA} is the mechanical outdoor air airflow rate [m^3/h], p is the penetration factor of particles through leaks in building envelopes and major openings (dimensionless, ranging from 0 to 1), Q_i is the infiltration airflow rate [m^3/h], E is the indoor emission rate [μg/h], Q_R is the recirculation airflow rate [m^3/h], η is the filter efficiency (dimensionless, ranging from 0 to 1), β is the first-order indoor loss