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Investigations of indoor air quality of large department store buildings in China based on field measurements

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ABSTRACT

This paper presents a large-scale field studies on the indoor air pollution in large multi-storey department store buildings in seven Chinese metropolitan cities. From the year 2013–2015, nine buildings equipped with centralized air-conditioning system were carefully selected for the onsite test. Results show that each building has diverse indoor thermal environment and concentrations of CO_2, formaldehyde and TVOC. Mean concentrations of CO_2, formaldehyde and TVOC in the measured buildings range from 560 to 997 ppm, 0.02–0.31 mg/m^3 and 0.074–0.636 mg/m^3 respectively. The highest rates of exceeding the standard limit in the tested buildings were found as 36.8% of CO_2, 53.2% of formaldehyde and 40.3% of TVOC. There are significant correlations between indoor and outdoor concentrations of CO_2, formaldehyde and TVOC. The pollutant concentrations are different in different merchandise sections. Furthermore, significant differences and colorations of the pollution concentration are revealed between that of aboveground and underground floors. A mathematical model for the calculation of the increment of fresh air for the underground floors of a department store building is proposed based on the theoretical analysis and the assumption of steady-state airflow condition. This model provides quantitative relations of a required amount of additional fresh air of the underground floor referencing to the aboveground floor of the same building. Based on this research, it is recommended that the factors of space functionality and usage as well as the location of under-aboveground floors of the department stores should be taken into account in the design and operation of the HVAC systems.

1. Introduction

In recent years, China is undergoing a series of major social changes including unprecedented and advanced urbanization [1–5]. The average expenditure of Chinese urban households is increasing, with consumption cost up to more than 20,000RMB per annum according to the China Statistical Yearbook [6]. Shopping has inevitably become one of the urban lifestyles and department store buildings, where people can purchase daily necessities, are gradually becoming a basic and indispensable element of the rapid urbanization [7–10]. With the demand of construction of shopping malls and the scarce of land resources [11–14], Developers take advantages of underground space, especially for commercial and retail buildings [15–18]. Large shopping center and department stores are usually equipped with central air-conditioning systems for heating, cooling and ventilation in order to provide customs with comfort indoor thermal environment. However, the issue of indoor air pollution in shopping malls has drawn public concerns.

Formaldehyde and volatile organic compounds (VOCs) are regarded as highly toxic and carcinogens sources that can cause respiratory illness [19,20]. Most VOCs are widely used in construction, furniture, textiles, carpentry and chemical industry [21,22]. High levels of formaldehyde and TVOC are risk factors to asthma and rhinitis, and may even lead to skin, melanoma, lung and endocrine-related cancers [23–30]. Moreover, indoor CO_2, formaldehyde and TVOC (Total Volatile Organic Compounds) are risk factors of Sick Building Syndrome (SBS) which have been regularly reported worldwide [31–34]. Evidences are reported that

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the value of pollutants including formaldehyde, TVOC and CO_2 exceeds the threshold ranging from 40% to 87% in some department store buildings [35–38].

Although studies have identified that the IAQ of underground spaces, especially underground malls, is worse than that in ground level spaces [39–45], the study of IAQ in multi-storey department store buildings and department stores with both underground and aboveground floors is still relatively limited. There are little first-hand onsite measurement data available for the analysis of the current situations of such large department store buildings.

The aim of this research is to investigate indoor air quality in multi-storey large department stores in the aboveground and underground floors through onsite measurements of CO_2, formaldehyde and TVOC. The analysis of the firsthand measured data will provide evidence of the current situation and be of useful to the improvement of the operation of HVAC systems in such buildings.

2. Methods

Onsite investigation and measurements were carried out during the period of 2013–2015. 4 capital cities namely Wuhan, Kunming, Changsha and Xi'an and three municipalities namely Shanghai, Tianjin and Chongqing were selected. These cities have high annual household consumption expenditure. They locates in three distinct climate zones named as the 'cold' zone (Tianjin and Xi'an), the 'hot summer and cold winter' zone (Shanghai, Wuhan, Changsha and Chongqing), and the 'mild' zone (Kunming). Being claimed as international metropolitan cities, Shanghai, Tianjin and Chongqing each has a relatively high level (above national average) of regional expenditure compared to the other four cities. The average annual regional urban household consumption expenditure of these 7 cities is close to the national average level (deviation less than 15%) according to National China Statistical Yearbook (2015) [6]. The large department store buildings selected in these 7 cities are regarded as representative.

2.1. Building information

9 large department stores in the Center Business District (CBD) were selected with similar building functionalities. The selection of the department store buildings considered factors of similar building scale, floor layout, HVAC systems, and the year of completion. All the selected buildings are categorized as large-scale department store building with more than 2000 m^2 floor area and a very similar open plan layout of the retail space. They all constructed between the years 2003–2013. Each building has some same internal usage area including cosmetic area, leather product area, and cloth area, etc. They all have the same type of centralized air-conditioning systems which run all year around. They all have two separate air-conditioning systems for underground and aboveground floors. All the buildings are far away from industry area so the industrial pollution could be disregarded. In each city, one or two large department store buildings of similar design were carefully selected. A total number of 9 department stores were studies. Table 1 lists the building information of the selected department stores.

2.2. On-site measurements

For each building, one typical weekday and one typical weekend were selected in every two months, so the whole measurement period lasted from about six months to fourteen months aimed to cover three typical seasons of winter, summer and spring/autumn. Building I in Xi'an only covered two typical seasons summer and spring/autumn due to the project management issue in the first season in winter. The onsite measurement was conducted on both weekdays and weekends over a total period of 6–12 days respectively, lasting from year 2013–2015(Table 2).

The Chinese Standard for Energy Efficiency Test of Public Buildings (JGJ.T 177-2009) [46] was used as a reference for the decision of the floors measured. The coverage floors include low, middle and high levels of each building. For each building, two to six measurement points were selected in each measured floor to ensure the representative number of 12–20 sampling points. The height of each sampling point was consistent with the human respiratory zone, i.e. between 1.2 and 1.5 m above the floor level. The measurement points avoided interference from ventilation vents, human activities and interior walls. The distance between the wall and measurement points was greater than 0.5 m. In addition, sampling sites were set in different merchandise sections of the buildings such as the clothing, cosmetics, catering, and leather products etc., and the sampling sections including all merchandise sections within the building. Outdoor measurements points were located about 30 m away from the entrance of each department store. All the measured parameters including temperature, humidity, CO_2, formaldehyde and TVOC were continuously measured throughout the day. On the testing day, the measurement started mainly at 10:30 o'clock after the department store was opened, and ended until it closed at about 20:00 or 22:00 in the evening upon to the closing hour of individuals. The total testing time was about 10–12 h, with 6–8 sets of sampling cycles within a day. Each sampling cycle lasted between 1.5 and 2 h for measuring all the parameters at the selected points inside and outside the building simultaneously. The measured floors and detailed information of sampling sites are listed in Table 3.

All the measurement instruments were calibrated as per the manufacturers' recommended calibration procedures to ensure accuracy and consistence of the measurements. Table 4 lists the instruments used in the test and theirs specifications. SPSS Version 21.0 software package was used for the data processing and statistics analysis. Correlation analysis and regression fitting was performed based on the data collected.

3. Results and analysis

3.1. The overall indoor thermal environment and pollution

A summary of the thermal parameters and concentrations of pollutants in the nine department store buildings is shown in Table 5. In the nine test buildings, Building H (in Chongqing) has the greatest temperature fluctuating ranging from 18.9 to 27.1 °C, whereas other buildings have either excessively low (building B,C,D,F,G in winter) or high (building A,B,C,D,E,F,G,I in summer) temperature. Building C (in Tianjin) and F (in Changsha) have the lowest 35.5% and highest 61.5% humidity respectively and almost every building has excessively low humidity (less than 30%, except building F and G) as well as excessively high humidity (higher than 70%, except building C). The mean values of the concentrations of pollution are from 0.02 to 0.31 mg/m^3 for formaldehyde, 560–997 ppm for CO_2 and 0.074–0.636 mg/m^3 for TVOC in the tested buildings. Some buildings exceeded the threshold recommended by the national standard Indoor Air Quality Standard (GB/T18883-2002) as 0.1 mg/m^3 for formaldehyde, 1000 ppm for CO_2 and 0.6 mg/m^3 for TVOC [47]. The percentages of exceeding the national standard limit of CO_2 in Building A, E, H and D are 36.8%, 26%, 18.6% and 12.2% respectively. Building A, D and E had relatively high daily CO_2 concentration exceeding 900 ppm. Building A has the highest daily formaldehyde of 0.31 mg/m^3 with 53.2% of test points exceeded the standard limit. Building D has the second highest daily formaldehyde concentration of 0.10 mg/m^3 with