Building and Environment 119 (2017) 140–152

Contents lists available at ScienceDirect

Building and Environment

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

A new method to assess infiltration rates in large shopping centers

Yuchen Shi [a], Xiaofeng Li [a, b, *], Haoru Li [a]

[a] Department of Building Science, School of Architecture, Tsinghua University, Beijing, 100084, China
[b] Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Beijing, 100084, China

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form
13 March 2017
Accepted 15 April 2017
Available online 18 April 2017

Keywords:
Deposition
Field test
Infiltration rate
Shopping centers
PM2.5

ABSTRACT

Large shopping centers integrate multiple functions within a single building, which typically results in high energy consumption. Building energy performance and indoor air quality are significantly dependent upon ventilation, which is influenced by uncontrolled air leakage (i.e. air infiltration) across the building exterior. In general, shopping centers in China are in a state of significant negative pressure due to the sub-optimal management of air conditioning operational systems. Therefore, an accurate estimation of the air infiltration rate is necessary to instruct operational management and to improve energy performance. Common infiltration rate testing methods often fail to continuously measure infiltration rates in large inner spaces for extended time periods. This paper presents a new methodology to assess the infiltration rate using the mass balance of particulate matters whose aerodynamic diameters are smaller than 2.5 μm (PM2.5). The deposition, generation and penetration of indoor PM2.5 are also considered. A field test is conducted in a large shopping center in Beijing (China), with the new method applied to assess the infiltration rate. The results are verified by the airflow mass balance throughout the entire building. Also, the methodology helps to determine the main sources of indoor PM2.5 as well as to instruct how indoor PM2.5 concentration can be effectively reduced.

1. Introduction

The large shopping center is an emerging type of large public building being built in cities across China. It integrates multiple functions within a single building, such as shopping, dining and entertainment. Current data shows that the total construction area for commercial complexes with large shopping centers will approach 100 million square meters by 2019 [1]. In general, large shopping centers are characterized by higher energy consumption for air conditioning than other types of public buildings [1]. The rapid development of large shopping centers is accelerating energy consumption for air conditioning systems. Therefore, it is important to identify viable ways to improve energy performance.

Uncontrolled air leakage across a building exterior is a primary reason for the excessive energy consumption of air conditioning systems [2]. In the United States of America, a simulation study found that improving airtightness of building envelopes resulted in a 3–36% energy saving potential [3]. In the cold regions of China, when the infiltration rate was reduced from 0.3 to 0.03 ach, the annual heating and cooling load in a public building was reduced by more than 40% [4]. There are various other negative consequences of air infiltration in public buildings, including compromised thermal comfort and adverse effects to normal operation of the ventilation system [5]. Also, indoor PM2.5 concentrations are highly correlated with outdoor concentration levels because of air infiltration [6]. This means that infiltration directly influences indoor air quality, especially when the outdoor air is highly polluted.

At present, most shopping centers in China are in a state of significant negative pressure and have large amounts of air infiltration. Fig. 1 shows the field test results of 16 shopping centers throughout China [7]. Here, 87.5% of the centers are in a state of negative pressure, with an average infiltration rate of 150×10^3 m^3/h. The deficiency of make-up air in kitchens is the primary reason for the huge air infiltration. E-commerce has had a significant impact on the retail industry, with catering services now becoming the main way to attract customers into large shopping centers. This results in increased cooking in open kitchens and requires larger amounts of exhaust air. Based on China's current standards, make-up air flow should be 80–90% of the exhaust air flow in a commercial kitchen [8]. However, the majority of restaurant owners in shopping centers cannot appropriately operate the make-up air system. As such, open kitchens and related services would cause

* Corresponding author. Department of Building Science, School of Architecture, Tsinghua University, Beijing, 100084, China.
E-mail address: xfli@mail.tsinghua.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.buildenv.2017.04.011
0360-1323/

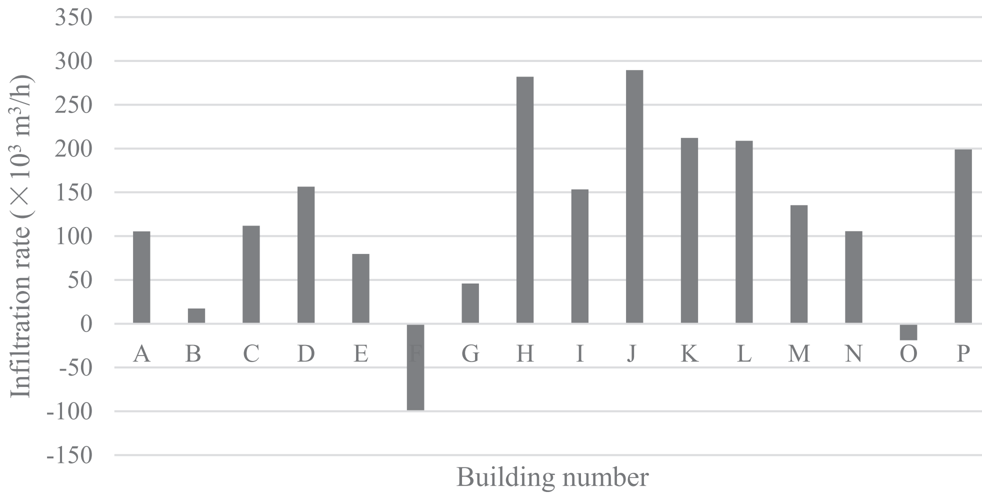

Fig. 1. Field test results of 16 shopping centers throughout China.

serious negative pressure throughout the entire building, resulting in a significant amount of air infiltration and excessive energy consumption. Hence, the assessment and monitoring of infiltration rates in shopping centers are necessary to instruct the operational management of air conditioning systems.

There are two standard methods to measure the infiltration rate: fan pressurization and tracer gas. The fan pressurization method involves the mechanical pressurization or depressurization of a building, then measuring the resulting air flow rates at given indoor-outdoor static pressure differences [9]. As a result, it does not measure air infiltration rates under normal climate conditions and building operation. The tracer gas method covers techniques that use tracer gas dilution for determining the air change rate of a single zone. These techniques include concentration decay, constant injection and constant concentration [10]. The decay method involves seeding the zone with a tracer gas, ensuring a uniform concentration within the zone and then analyzing the decay of the concentration over a given time period. Other methods use the constant injection of a tracer gas or a constant concentration. Heidt and Werner [11] concluded that the decay method was more suitable for measuring air exchange rates of relatively tight spaces, whereas the constant injection method was more suitable for ‘leaky’ spaces. The tracer gas method has been used in office buildings [12–14], residential buildings [15–18], student dormitories [19] and motor vehicles [20]. However, for large shopping centers, the tracer gas method does not seem suitable due to the huge consumption of tracer gas and also the high implementation costs. Sulfur hexafluoride (SF_6) and carbon dioxide (CO_2) are two kinds of commonly used tracer gases. Taking CO_2 as an example, under the CO_2 constant injection method in a large building with a volume of 4×10^5 m^3, the ASHRAE suggests that the difference of indoor and outdoor CO_2 volume fraction be no less than 700 ppm [21]. Here, according to Eq. (1) [22]:

$$N = \frac{F_{CO_2}}{(c_1 - c_e)V_Z} \tag{1}$$

where$N$ is the air change rate, h^{-1}; F_{CO_2} is the CO_2 release rate, m^3/h; c_1 is the volume fraction of indoor CO_2, ppm; c_e is the volume fraction of outdoor CO_2, ppm; andV_Z is test area volume, m^3. Now, the consumption of CO_2 can be calculated. Assuming the air change rate is 1.5 h^{-1} in a large building, then 420 m^3/h CO_2 gas or 750 kg/h dry ice would be consumed in each experiment. Here, the storage and release of such amounts of tracer gas is difficult. Furthermore, indoor CO_2 concentration is significantly influenced by human release and SF_6 is a very strong greenhouse gas. Hence, these two tracer gases are not suitable for assessing and monitoring the infiltration rate in shopping centers.

Another method to assess the infiltration rate is using the indoor and outdoor airflow mass balance. It's based on the principle where a building is in steady state, when airflow coming into the building equals to that going out of the building. Thus, the infiltration rate can be calculated by knowing the inlet and outlet air flow rates. However, when this method is used in large shopping centers the workload of measurement will be tremendous, because there are over 50 air handling units (AHUs) and over a hundred outlets. The measurement will therefore require a large number of testers or take days, and the operating state of the HVAC system may change during the process. Hence, this method is not applicable in our study.

This paper proposes a new calculation method to assess the infiltration rate in large shopping centers based on the mass balance of particulate matters (PM). Given the ubiquity of PM in the outdoor environment and being cost-free, this method is able to avoid the disadvantages of the tracer gas and airflow mass balance method. However, unlike commonly used tracer gases, the deposition, resuspension and penetration of indoor particulate matters cannot be neglected. According to previous studies, between the diameter range of 0.3–10 μm, larger particles are easier to be deposited and resuspended and more difficult to penetrate [23–28], which will influence the accuracy of the new method. Thus, smaller particles are a better choice for our study. Besides, since people pay more and more attention to the hazy weather, the measuring instruments and on-line monitoring of PM2.5 are universal and of mature technology. Hence, PM2.5 are chosen to establish the mass balance. After the new method is established, a field test of the infiltration rate is conducted in a large shopping center in Beijing (China). Then the airflow mass balance is used to verify the result calculated by the PM2.5 mass balance method. This new method makes the assessment of infiltration rates in large shopping centers more feasible from both an implementation and costs perspective.

2. Methodology

2.1. PM2.5 mass balance

Taking internal building space as a control body, the airflows