A New Method to Assess the Infiltration Rate in Large Commercial Complex in Beijing, China

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Abstract

In China, large commercial complex is a new type of building with complicated type of business and high energy consumption. The energy performance of building significantly depends on the ventilation, which is affected by air infiltration through the uncontrolled air leakage across the building envelope. It is important for improving the building energy performance and reducing the air conditioning load to learn the infiltration rate in a commercial complex. Currently, the testing method of infiltration rate commonly used in some cases fails to measure the infiltration rate in a large commercial building continuously for a period of time. In this paper, a new method using the principle of mass balance relationship between indoor and outdoor particles was put forward. Then a field testing was conducted in a commercial complex in Beijing, China and the calculation result of infiltration rate based on the measurement data using the new method was verified according to airflow mass balance in the whole building. This method makes it easier to assess the infiltration rate in a large commercial complex and learn the change of infiltration rate in a period time. It can also help find out the main sources of indoor particle and improve the indoor air quality.

Keywords: Infiltration rate; PM$_{2.5}$ mass balance; Commercial complex; Field testing method

1. Introduction

As a new type of large-scale public building, large commercial complex provides dining, entertainment and exhibition services in a single building and now emerges in more and more cities. However, almost all of the...
buildings have the signature of variable types of function and high power density, making the energy consumption of air conditioning in the commercial complex appear much higher than in the ordinary public building. According to the statistics, in China the total floor area of the large-scale commercial complexes intended to be built in the next 5 years will come to 100 million square meters [1], bringing about large amount of energy consumption. It is important to reduce the air conditioning load and improve the building energy performance.

The energy performance of buildings significantly depends on the ventilation, which is affected by air infiltration from the outside through the uncontrollable air leakage across the building envelope [2]. Infiltration in commercial buildings can have many negative consequences, including reduced indoor thermal comfort and increased building energy consumption [3]. In the U.S. a series researches have been conducted using simulation tool to compare the energy use for the buildings at a target tightness level relative to a baseline level based on measurements in existing buildings and the predicted potential annual heating and cooling energy cost savings ranged from 3% to 36% [4]. In Sweden, the peak load of a house was reduced by 28.7% when the infiltration rate was decreased from 0.2 ach to 0.1 ach [5]. In cold region of China, the annual heating and cooling load in a public building was reduced by 40.44% when the infiltration rate was decreased from 0.3 ach to 0.03 ach [6]. Besides, infiltration may bring about interference with the proper operation of mechanical ventilation systems, degraded indoor air quality (IAQ), moisture damage of building envelope components [7]. It is important to learn the infiltration rate in a building. However, evaluating the infiltration rate is a complex task while the infiltration can be easily affected by building envelope construction, type and use of the doors, and HVAC system operation.

Currently, there are two different standard methods to measure the infiltration through a building envelope: the fan pressurization method and the tracer gas dilution method [2]. The fan pressurization method evaluates the air leakage characteristics from the airflow rate at given indoor-outdoor static pressure differences based on mechanical pressurization or de-pressurization of a building. Nevertheless, the fan pressurization method does not measure air leakage rate under normal weather conditions and building operation [8]. The tracer gas dilution method assesses the air change rate of a building making use of tracer gas concentration through three different techniques: concentration decay, constant injection and constant concentration [9]. There exits researches on infiltration using tracer gas method in office buildings [10], residential buildings [11], and student dormitories [12]. However, if the building has large space the tracer gas method seems to be not suitable on accounts of the large usage of the tracer gas.

As previously mentioned, a commercial building is usually ventilated using two mechanisms: mechanical ventilation and infiltration. Outdoor air containing outdoor-originated particles comes into the room through both of the ventilation patterns. Filters in mechanical ventilation system can remove part of the outdoor particle depending on the filter efficiency. Therefore, the outdoor particle directly transported into the indoors through infiltration, the outdoor-originated particle filtered by filters in mechanical systems, along with the indoor particle sources influence the indoor particle concentration. In this paper, a new method to assess the infiltration rate in large commercial complex was put forward based on mass balance of particles with aerodynamic diameters smaller than 2.5 μm (PM$_{2.5}$). Then field testing of ventilation and particles was conducted in a commercial complex in Beijing, China. The airflow mass balance was used to verify the calculation results from the particle mass balance method, making it applicable in practice. This new method makes it easier to assess the infiltration rate in a large commercial complex when fan pressurization method and tracer gas method are infeasible with large indoor space in a building.

2. Methodology

2.1. Airflow mass balance

The airflow mass balance on the combined building and HVAC system in Fig.1 can be expressed as the following equation:

$$Q_{ma} + Q_{inf} = Q_{exf} + Q_{me}$$

where $Q_{ma}$ is the makeup airflow, $Q_{inf}$ is the infiltration airflow due to natural convection, $Q_{exf}$ is the exfiltration airflow due to natural convection, and $Q_{me}$ is the airflow mechanically exhausted to the outdoors.
In Equation (1), the net infiltration or exfiltration air rate can be calculated according to the air flow mass balance equation after the airflow from mechanical ventilation system, $Q_{ma}$ and $Q_{me}$, are measured.

2.2. Particle mass balance

The particle mass balance within the indoor space in Figure 1, with input and output from the HVAC system, is given mathematically by Thornburg et al. [13]:

$$V \left( \frac{dC}{dt} \right) = PC_{out}Q_{inf} + C_{hv}Q_{hv} + G - CA_{d}v_{d} - CQ_{ef} - CQ_{ra} - CQ_{me}$$ \hfill (2)

where $V$ is the building volume, $C$ is the indoor particle concentration, $t$ is time, $P$ is the fraction of particles that penetrate the building envelope due to natural convection, $C_{out}$ is the outside particle concentration, $G$ is the indoor generation rate, $A_{d}$ is the surface-area available for deposition, $v_{d}$ is the deposition velocity, $C_{hv}$ is the particle concentration coming from the HVAC system, $Q_{hv}$ is the airflow from the HVAC system, $Q_{ra}$ is the return airflow from the room to the HVAC system.

Then on the HVAC system, the particle mass balance equation can be expressed as:

$$C_{hv}Q_{hv} + V_{hv} \frac{dC_{hv}}{dt} = (1 - \eta)C_{out}Q_{ma} + CQ_{ra} - \eta CQ_{me}$$ \hfill (3)

where $V_{hv}$ is the volume of the HVAC system, $\eta$ is the filtration efficiency of the HVAC system. In this equation, only the efficiency of HVAC filter is considered.

Substituting Equation (3) into Equation (2) yields:

$$V \left( \frac{dC}{dt} \right) + V_{hv} \left( \frac{dC_{hv}}{dt} \right) = PC_{out}Q_{inf} + G - CA_{d}v_{d} - CQ_{ef} + (1 - \eta)C_{out}Q_{ma} - \eta CQ_{ra} - CQ_{me}$$ \hfill (4)
For $V_{hv}$ is much smaller than $V$ and the change of $C_{hv}$ over time can be neglected, Equation (4) can be simplified as:

$$V \left( \frac{dC}{dt} \right) = P C_{out} Q_{inf} + G + (1 - \eta) C_{out} Q_{ma} - \eta C_{out} Q_{ra} - C_{out} Q_{me} - C_{out} Q_{exf}$$

(5)

Then the final steady-state indoor particle concentration is:

$$C_f = \frac{C_{out} \left[ P Q_{inf} + (1 - \eta) Q_{ma} \right] + G}{Q_{exf} + \eta Q_{ra} + Q_{me} + A_f v_d}$$

(6)

Substituting Equation (1) into Equation (6) yields:

$$C_f = \frac{C_{out} \left[ P Q_{inf} + (1 - \eta) Q_{ma} \right] + G}{Q_{ma} + Q_{inf} + \eta Q_{ra} + A_f v_d}$$

(7)

Then the infiltration rate can be expressed as:

$$Q_{inf} = \frac{[C_f - (1 - \eta) C_{out}] Q_{ma} + \eta C_f Q_{ra} + C_f A_f v_d - G}{P C_{out} - C_f}$$

(8)

In a particular commercial building, the filter efficiency, surface-area available for deposition, deposition velocity and the penetration factor can be usually regarded as constant parameters. The airflow from mechanical ventilation system is related with operation mode of the ventilation unit. Then the infiltration rate can be calculated after the particle concentration is measured. If the particle concentration can be measured continuously, the infiltration rate in a period can be calculated.

In order to verify the feasibility of the infiltration rate calculation method using indoor and outdoor particle concentration, a field testing was conducted in a large commercial complex in Beijing, China. The commercial complex has a total area of 87,000 square meters with three levels on the ground and one level underground, including retailing shops, restaurants, supermarket and other business. The commercial complex is also connected with an office building through a corridor.

3. Results

3.1. Airflow mass balance

Fig.2 shows the measured airflow mass balance in the commercial complex. The total makeup airflow from the HVAC systems and other mechanical ventilation systems was 146,000 m$^3$/h. The total exhaust airflow from the mechanical ventilation systems was 349,000 m$^3$/h. Because of the differential pressure between the commercial complex and the connected office building, the airflow coming into the commercial complex through the passway was 24,000 m$^3$/h. Then according to the airflow mass balance in the commercial complex, the outdoor airflow infiltrating into the commercial complex should be 179,000 m$^3$/h. The results showed that there existed large amount of infiltration airflow in the commercial complex on account of the huge difference between the makeup airflow and the exhaust airflow.
Fig. 2. Measured data of airflow mass balance in the commercial building (HVAC: makeup airflow from HVAC system; Infiltration: calculated results according to the airflow mass balance; Passway: airflow through the passway with the office building; MA_R: makeup airflow from ventilation system in the restaurants; ME_R: exhaust airflow from the mechanical ventilation system in the restaurants; others: exhaust airflow through other ways).

3.2. PM$_{2.5}$ mass balance

Then the concentration of PM$_{2.5}$ was measured in the tested building. Based on prior analysis, the indoor particle concentration is mainly influenced by the infiltration rate and the filter efficiency. Fig. 3 displays the measured data of PM$_{2.5}$ concentration indoors and that coming from the HVAC system in different floors, as well as PM$_{2.5}$ concentration outdoors. The indoor particle concentration on the first floor was much higher than that from the
HVAC systems while the indoor particle concentration on other floors was similar with the concentration coming from the HVAC systems. It is obvious that infiltration was mainly from the doors or other unintentional cracks on the first floor. Particle from the infiltration was not filtered, leading to indoor particle concentration on the first floor much higher than that from airflow of the HVAC systems. The indoor particle concentration on other floors was mainly influenced by particles from the HVAC systems. Therefore, the first floor of the commercial complex was regarded as a control volume to calculate the infiltration using Equation (8). It was assumed that the particle transfer between the first floor and the second floor reached a balanced state. Table 1 shows the input parameters in the process of calculation using equation.

Table 1. Input parameters in process of calculating infiltration rate.

| Parameters                          | Symbols | Values  |
|-------------------------------------|---------|---------|
| Penetration factor                  | $P$     | 1       |
| Generation rate ($\mu$ g/h)         | $G$     | 0       |
| Surface-area available for deposition (m$^2$) | $A_s$   | 18856   |
| Deposition velocity (m/h)           | $v_d$   | 0.1     |
| AHU filter efficiency (%)           | $\eta_{AHU}$ | 25     |
| PAU filter efficiency (%)           | $\eta_{PAU}$ | 42     |
| Makeup airflow (F1) (m$^3$/h)       | $Q_{ma}$ | 31862   |
| Return airflow (F1) (m$^3$/h)       | $Q_{re}$ | 185995  |

In Table 1, the filter efficiency and the airflow were measured in the commercial complex. The surface-area available for deposition was calculated according to the floor plan. For there was no particle source in the commercial complex, the generation rate of the particle was set to be 0. The penetration factor and the deposition velocity were recommended by Thatcher and Layton [14] and Thornburg et al. [13]. Table 2 shows the infiltration rate respectively calculated according to airflow mass balance and particle mass balance. As mentioned before, the infiltration rate was 179,000 m$^3$/h based on airflow mass balance in the whole commercial complex. The infiltration rate calculated by particle mass balance equation was 168,000. The relative error between the calculations was 9.58% which was within the range of allowable errors, making it applicable in practice.

Table 2. Comparison of infiltration rates calculated with two methods.

| Methods             | Infiltration rate ($10^4$ m$^3$/h) | Relative error |
|---------------------|------------------------------------|----------------|
| Airflow mass balance| 17.9                               | 9.58%          |
| Particle mass balance| 16.8                               |                |

4. Conclusions

In this paper, a new method to assess the infiltration rate in large commercial complex was put forward based on mass balance of particles with aerodynamic diameters smaller than 2.5 $\mu$m (PM$_{2.5}$). First, a field testing of airflow mass balance was conducted in a commercial complex in China to calculate the infiltration rate. Then particle concentration was measured to verify the equation of infiltration rate calculation based on the particle mass balance. Data showed that the calculation results of infiltration rate using the two methods was almost the same and the relative error was within the range of allowable errors, making it applicable in practice. This method makes it easier to assess the infiltration rate in a large commercial complex and learn the change of infiltration rate in a period time. It can also help find out the main sources of indoor particle and improve the indoor air quality.
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