Effect of mechanical ventilation on air infiltration rate in a concert hall

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Abstract. Due to high occupant density, fresh air is essential for audience in a concert hall. Generally, mechanical ventilation system is used to supply outdoor fresh air. Apart from that, uncontrolled air leakage across building exterior (i.e., air infiltration) is also a source of outdoor fresh air. Though ASHRAE requires a positive pressure (i.e., zero infiltration rate) for mechanically ventilated rooms, positive pressure is difficult to be maintained under poor building airtightness or low mechanical ventilation rates. When the positive pressure is not achieved, the existence of air infiltration brings about outdoor air pollutants infiltrating indoors and excessive fresh air cooling/heating load. Therefore, to maintain a good indoor environment and an appropriate fresh air rate, the effect of mechanical ventilation on air infiltration rate must be figured out. This study investigates the variation laws of infiltration rate with mechanical ventilation rate in a concert hall. Infiltration rates under different mechanical ventilation rates were measured based on the particle mass balance method. It is concluded that the relationship between the two rates conforms to the theoretical model proposed by the authors’ previous study.

1. Introduction

To maintain a satisfying indoor air quality, sufficient fresh air for building occupants is vital, especially for audience in a concert hall due to the high occupant density [1]. China’s standard of fresh air rate for theatre buildings (including concert halls) is 15 – 25 m³/h per person [2]. To reach the standard, mechanical ventilation systems are generally used. Actually, apart from mechanical ventilation, air infiltration, which means the uncontrolled air leakage across the building envelop, is also a source of outdoor fresh air.

In order to limit the infiltration of outdoor air pollutants and high dew point air, ASHRAE requires that mechanically ventilated rooms should keep a positive pressure (i.e., zero infiltration rate) [3, 4]. However, many studies have indicated that rooms at positive air pressure are difficult to be achieved if building airtightness is poor or mechanical ventilation rate is low [5-7]. During the past decade, outdoor haze pollution in China is very serious [8]. When a positive room pressure is not achieved, outdoor air pollutants get into the indoor environment along with the infiltrated air [6, 9], which threatens the health of indoor occupants. In addition, considering that mechanical ventilation rate is designed according to building occupants and indoor air quality, when mechanical ventilation rate is not enough to keep positive room pressure, excessive ventilation will occur due to the existence of air infiltration [10], which causes energy loss. Therefore, to maintain a good indoor environment and an appropriate fresh air rate, the relationship between mechanical ventilation and air infiltration rates must be figured out.

In order to figure out the relationship between the two rates, infiltration rates under different mechanical ventilation rates need to be measured. Mechanical ventilation rates can be measured in air ducts using an anemometer. The most commonly used method to assess infiltration rate is the tracer gas method [11]. However, for large spaces such as concert halls, tracer gas method is expensive and complex to implement. Hence, the authors have proposed a simpler method to assess infiltration rate for
large space buildings based on the mass balance of particulate matters [12], which is adopted by this study.

In our previous study [13], the authors theoretically deduced the relational expressions between infiltration and mechanical ventilation rates, and validated the theoretical derivations by infiltration rate tests in offices rooms. We found that a mechanical ventilation rate of up to 3.2 times the initial infiltration rate is required to maintain a positive room pressure. However, there is a lack of study on this issue when it comes to large space rooms such as concert halls. This study investigates the variation laws of infiltration rate with mechanical ventilation rate in a concert hall with an internal height of up to 20 m. Infiltration rates under different mechanical ventilation rates were measured based on the particle mass balance method. The measured results were compared with our previous derivations to proof the applicability of our proposed models for large space rooms.

2. Method

2.1. Particle mass balance method

Taking the internal room space as a control body, the particle mass balance is shown in Figure 1. The steady-state particle mass balance equation is expressed as

\[
Q_{in}c_{out} + Q_{mf}(1 - \eta_{mf}) = Q_{re}\eta_{re}c_{in} + (Q_{in} + Q_{mf})c_{in} + Kc_{in}
\]  

(1)

where \(Q_{in}\) is infiltration rate, m³/h; \(c_{out}\) is outdoor particle concentration, μg/m³; \(Q_{mf}\) is mechanical fresh air rate, m³/h; \(\eta_{mf}\) is filtration efficiency of mechanical fresh air unit, dimensionless; \(Q_{re}\) is mechanical return air rate, m³/h; \(\eta_{re}\) is filtration efficiency of mechanical return air unit, dimensionless; \(c_{in}\) is indoor steady-state particle concentration, μg/m³; \(K\) is particle deposition rate, h⁻¹; and \(V\) is volume of the control body, m³.

According to Eq. (1), infiltration rate is calculated by the following equation:

\[
Q_{in} = \frac{Q_{re}\eta_{re}c_{in} + Q_{mf}c_{in} - Q_{mf}(1 - \eta_{mf})c_{in}}{c_{out} - c_{in} + KV}
\]  

(2)

Due to people’s sustained attention to fine particulate matters (particles with a maximum diameter of 2.5 μm, abbreviated as PM2.5) which can be inhaled into lungs, the measuring instruments and on-line monitoring of PM2.5 are prevalent and of mature technology [14]. Therefore, PM2.5 is chosen to establish the mass balance. According to Eq. (2), when indoor and outdoor particle concentrations, mechanical ventilation rates, filtration efficiencies, room volume, and deposition rate are determined, infiltration rate can be calculated. Among them, indoor and outdoor particle concentrations, mechanical ventilation rates, filtration efficiencies, and room volume are obtained by measurements. Researchers have found that indoor deposition rate is 0 – 0.5 h⁻¹ for PM2.5, and the calculated infiltration rate is not sensitive to deposition rate when mechanical ventilation rate and filtration efficiency are high [15, 16]. Hence, PM2.5 deposition rate is set to 0.25 h⁻¹ in this study.

**Figure 1.** Indoor particle mass balance.
2.2. Relationship between the two rates
To illustrate the relationship between infiltration and mechanical ventilation rates, the infiltration ratio (hereinafter, INF ratio) and mechanical ventilation ratio (hereinafter, MV ratio) are defined as follows:

$$INF_{ratio} = \frac{Q_{inf}}{Q_{inf,0}}$$  

$$MV_{ratio} = \frac{Q_{mf}}{Q_{inf,0}}$$

where $Q_{inf,0}$ is the initial infiltration rate when the room is not supplied with mechanical fresh air, m$^3$/h. In other words, the initial infiltration rate is calculated when $Q_{mf}$ in Eq. (2) is zero:

$$Q_{inf,0} = \frac{q_{pre}r_{pre}c_{in}+kVc_{in}}{c_{out}-c_{in}}$$

Relationship between the two rates is figured out by the following steps:
1. Measure the space volume of the concert hall.
2. Measure the initial infiltration rate $Q_{inf,0}$ when mechanical fresh air is not supplied.
3. Under the same weather conditions with Step 2, supply a certain amount of mechanical fresh air $Q_{mf}$ and measure the infiltration rate $Q_{inf}$.
4. Repeat Steps 2 and 3, multiple sets of INF and MV ratios were obtained to draw the INF – MV curve.

3. Results
3.1. Measuring results
The measured concert hall (as shown in Figure 2) has an internal height of 19.8 m, a volume of 6950 m$^3$ and 510 seats. In order to obtain the relationship between infiltration and mechanical ventilation rates, infiltration rates under different mechanical ventilation rates were measured based on the particle mass balance method. Instruments used in the measurements are listed in Table 1.

The concert hall has two air handling units (AHUs), one for stage area (AHU1) and another for audience area (AHU2). The stage area is sided air-supplied. Air inlets are on one side of the stage, with a height of 15 m, and air outlets are on the other side, with the same height. The audience area uses seat air supply, with a big static pressure chamber under the seats, which contributes to the uniform of indoor air flow field. Mechanical ventilation rates of AHUs were measured in air ducts using hot wire anemometer. Filtration efficiency was measured by PM2.5 monitors. There were twelve measuring points indoors for PM2.5 concentrations and two outdoors. Indoor PM2.5 measuring points were evenly distributed. The indoor distribution of PM2.5 concentration was measured to be uniform, which was because the air change rate of the concert hall was as high as 4 ACH (air change per hour).

![Figure 2. The measured concert hall.](image)
Table 1. Instrument list.

| Instrument               | Model               | Accuracy                  | Usage                                           |
|--------------------------|---------------------|---------------------------|-------------------------------------------------|
| Tape measure             | Tajima Hilock-25    | ± 0.5 mm                  | Measuring space volume and mechanical ventilation rates |
| Hot wire anemometer      | TSI 962             | ± 0.015 m/s or ± 3% of reading | Measuring mechanical ventilation rates         |
| PM2.5 concentration monitor | TSI AM510         | /                         | Measuring indoor and outdoor PM2.5 concentrations |

Measurements were conducted on May, 2017 and March to June, 2019. First, the two AHUs were adjusted to ‘All return air’ model, under which circumstances there was no mechanical fresh air and the initial infiltration rate was measured. Then, AHU2 was adjusted to ‘Fresh and return air’ model, with AHU1 unchanged. In this case, different amount of mechanical fresh air was supplied to the concert hall by adjusting the fresh and return air valves. Infiltration rate under certain mechanical fresh air rate was measured. Measuring results on May 3, 2017 are listed in Table 2 for example. Duplicate measurements were conducted on March to June, 2019 and multiple sets of INF and MV ratios were obtained. Results of INF and MV ratios are listed in Table 3, which indicates that the higher the mechanical ventilation rate is, the lower the infiltration rate becomes. When MV ratio is around 2, there is still air infiltration; when MV ratio is higher than 5, positive pressure is achieved in the concert hall.

Table 2. Results on May 3, 2017.

| Ventilation condition | All return air | Fresh and return air |
|-----------------------|----------------|----------------------|
| Mechanical return air rate of AHU1, $Q_{re1}$ (m$^3$/h) | 13213 | 13213 |
| Mechanical return air rate of AHU2, $Q_{re2}$ (m$^3$/h) | 14461 | 3746 |
| Mechanical fresh air rate of AHU2, $Q_{mf}$ (m$^3$/h) | 0 | 11354 |
| Filtration efficiency | 75.5% | 75.5% |
| Outdoor PM2.5 concentration, $c_{out}$ (μg/m$^3$) | 108 | 98 |
| Indoor steady-state PM2.5 concentration, $c_{in}$ (μg/m$^3$) | 10 | 11 |
| (Initial) Infiltration rate, $Q_{inf,0}$ or $Q_{inf}$ (m$^3$/h) | $Q_{inf,0}$=2259 | $Q_{inf}$=72 |

Table 3. Results of MV and INF Ratios.

| Date                    | May 3, 2017 | March 8, 2019 | March 19, 2019 | March 26, 2019 | April 3, 2019 | June 7, 2019 |
|-------------------------|-------------|---------------|----------------|----------------|---------------|--------------|
| Initial infiltration rate, $Q_{inf,0}$ (m$^3$/h) | 2259 | 6044 | 6659 | 2063 | 1619 | 2449 |
| Mechanical fresh air rate, $Q_{mf}$ (m$^3$/h) | 11354 | 11838 | 15745 | 15745 | 10566 | 2355 |
| Infiltration rate, $Q_{inf}$ (m$^3$/h) | 72 | 1547 | 987 | 16 | 33 | 1572 |
| MV ratio                | 5.03 | 1.96 | 2.36 | 7.63 | 6.53 | 0.96 |
| INF ratio               | 0.03 | 0.26 | 0.15 | 0.01 | 0.02 | 0.64 |
3.2. Compared with theoretical models

Main factors causing air infiltration in buildings are stack effect and wind pressure [4]. In order to use the particle mass balance method to assess infiltration rate, the measurements above were conducted during PM2.5 pollution weathers. Horizontal static wind is one of the main reasons for the formation of particle pollution [17]. Therefore, during the measuring period, outdoor wind speed was low and stack effect was the main factor causing air infiltration.

In our previous study [13], the authors theoretically deduced the relational expressions between infiltration and mechanical ventilation rates. We found that INF ratio is negatively correlated to MV ratio; when MV ratio is higher than a certain value, INF ratio can be reduced to zero. The relation curve between MV and INF ratios is influenced by ventilation model (stack effect and wind dominant ventilation models) and the size of cracks on external windows or doors. For the measured concert hall, infiltration is mainly caused by stack effect and the width-height ratio of external door crack is 0. According to theoretical derivations [13], the relation curve between MV and INF ratios is illustrated in Figure 3. Also, the measured values of MV and INF ratios in Table 3 are compared with the theoretical curve, which shows that the measured values fit well with the theoretical curve. The R-square between the measured values and theoretical curve is 0.90.

In summary, the results demonstrate the relationship between infiltration and mechanical ventilation rates and prove the applicability of our proposed models for large space rooms such as concert halls.

![Figure 3. Comparison of measured and theoretical values.](image)

4. Conclusion and Discussion

Mechanical ventilation system is commonly used to supply fresh air in concert halls. Though ASHRAE requires a positive pressure for mechanically ventilated rooms, actually the positive pressure is difficult to be achieved, which will bring about the problems of outdoor air pollutants and excessive ventilation. In order to maintain a good indoor environment and an appropriate fresh air rate, this study investigates the variation laws of infiltration rate with mechanical ventilation rate in a concert hall. Infiltration rates under different mechanical ventilation rates were measured based on the particle mass balance method. It is concluded that infiltration rate is negatively correlated to mechanical fresh air rate, and when the ratio between mechanical fresh air and initial infiltration rates is high enough, positive room pressure can be maintained. Also, the measured results conform to our previous theoretical derivations, which proves the applicability of our proposed models for large space rooms.

In future studies, more data need to be obtained when MV ratio is within 0 to 2 to better prove the applicability of the theoretical model. Meanwhile, the results of this study can be used as a guidance for optimizing ventilation rates and indoor air quality for concert halls.
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