Annual Energy Simulation for Two Indoor Air Purification Strategies

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Introduction

In non-centralized air-conditioned buildings (NAC buildings), two indoor air purification devices can be employed to simultaneously satisfy fresh air and indoor particulate matter (PM) concentration requirements, including air purifiers (APs) and fresh air units (FAUs). When using APs, open-window ventilation should be combined to supply fresh air. When using FAUs, a positive room pressure is required according to relevant standard to prevent outdoor pollutants from infiltrating into the indoor environment (ASHRAE, 2016).

From the perspective of annual energy consumption, this study aims to determine which of the two strategies—APs combined with open-window ventilation (AP-Mode) and FAUs combined with positive pressure control (FAU-Mode)—is more energy-saving to simultaneously supply adequate fresh air and remove indoor PM for NAC buildings. Based on the mass balance principle of indoor particulate matter, the relationships among the fresh air supply rate, PM2.5 I/O ratio, and clean air delivery rate (CADR) of APs used in the AP-Mode or FAUs used in the FAU-Mode are investigated. Accordingly, the annual energy consumptions of the two modes are simulated and compared using the outdoor PM2.5 concentration data of Beijing, Shanghai, and Guangzhou in 2015-2017. Based on the simulation results, optimal air purification strategies for NAC buildings in different cities of China are determined.

Methods

PM2.5 mass balance equation

For a room in a NAC building, the indoor PM2.5 mass balance equation for the steady state is expressed as (Thatcher and Layton, 1995)

$$PN_{inf}c_{out} + N_{nf}c_{out} + N_{mf}(1-\eta_{mf})c_{out} = (N_{inf} + N_{nf} + N_{mf})c_{in} + N_{CADR}c_{in} + Kc_{in} \quad (1)$$

where P is the penetration factor, dimensionless; N_{inf} is the air infiltration rate, h^{-1}; c_{out} is the outdoor PM2.5 concentration, μg/m^3; N_{nf} is the natural fresh air exchange rate by open-window ventilation, h^{-1}; N_{mf} is the mechanical fresh air exchange rate by FAU, h^{-1}; η_{mf} is the filtration efficiency of the FAU, dimensionless; c_{in} is the indoor PM2.5 concentration, μg/m^3; N_{CADR} is the clean air exchange rate of the AP, which is the CADR divided by room volume, h^{-1}; and K is the PM2.5 deposition rate, h^{-1}. In addition, the CADR of an AP or FAU is defined as the product of its air supply rate and filtration efficiency.

When the AP-Mode is used, $N_{inf} = 0$ and $N_{mf} = 0$. Equation (1) can be simplified as follows:

$$I/O_{ratio} = \frac{N_{nf}}{N_{nf} + N_{CADR} + K} \quad (2)$$

where I/O_{ratio} is the PM2.5 I/O ratio, which is the ratio of indoor and outdoor PM2.5 concentrations, dimensionless.

When the FAU-Mode is used, $N_{inf} = 0$, $N_{nf} = 0$ and $N_{CADR} = 0$. Equation (1) can be simplified as follows:

$$I/O_{ratio} = \frac{N_{mf}(1-\eta_{mf})}{N_{mf} + K} \quad (3)$$

Then the CADRs of the devices used in the two modes can be calculated using Equations (2) and (3) when the PM2.5 I/O ratio and fresh air requirement are determined.

Annual energy consumption simulation

The energy consumption of the AP-Mode or FAU-Mode includes the operating energy consumption of the APs or FAUs, and the fresh air cooling/heating load. The two modes are compared when supplying the same amount of fresh air. Therefore, the fresh air load is the same and only the operating energy consumption is considered.

China's national standard for air cleaners (GB/T18801-2015) defines the cleaning energy efficiency as follows (AQSIQ, 2015):

$$\eta = \frac{CADR}{P_{elec}} \quad (4)$$

where η is the cleaning energy efficiency, m^3/(W·h) and P_{elec} is the air cleaner electric power, W.

The annual energy consumptions of the two modes are simulated using the outdoor PM2.5 concentration data of three cities in China that are suffering from different degrees of PM pollution, including Beijing, Shanghai, and Guangzhou. The simulations are based on Equation (4) and the following assumptions:

a) APs and FAUs operate 10 hours a day.

b) Indoor target PM2.5 concentration is not guaranteed during the ten days when the outdoor PM2.5 concentrations are highest.

c) APs have six adjustable CADR levels (or air supply rates) which are used for different degrees of outdoor PM2.5 pollution:

   Levels I-VI are used when daily average outdoor PM2.5 concentrations are 15 - 35 μg/m^3, 35 - 50 μg/m^3, 50 - 75 μg/m^3, 75 - 100 μg/m^3, 100 - 200 μg/m^3, 200 - 300 μg/m^3, respectively.

d) The filtration efficiency of a FAU is determined by the highest daily average outdoor PM2.5 concentration except during the ten days mentioned in assumption b).

e) The cleaning energy efficiency is 5 $m^3/(W \cdot h)$ as recommended by GB/T18801-2015 for energy-efficient air cleaners.

f) Room area is 80 m^2 and room height is 3 m.

Key outcomes

Outdoor PM2.5 concentration

The daily average outdoor PM2.5 concentration data for Beijing, Shanghai, and Guangzhou in 2015-2017 is collected for the simulation, which is issued by US Department of State (http://www.stateair.net/web/post/1/1.html). The outdoor PM2.5 concentration distribution is shown in Figure 1. The annual average outdoor PM2.5 concentrations of the three cities in 2015-2017 are from 35 $\mu g/m^3$ to 82 $\mu g/m^3$. Among them, Beijing is the most air-polluted city, but the pollution degrees are declining from 2015 to 2017. Shanghai also has a declining trend of PM2.5 pollution. The outdoor PM2.5 concentration of Guangzhou is the lowest and does not change much during the three years, thus, only the data of 2016 is collected.

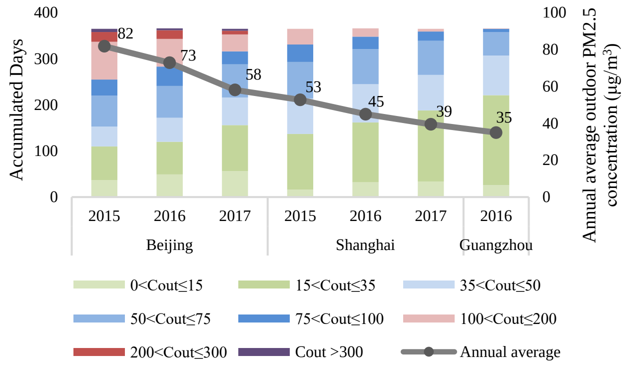

Figure 1: Outdoor PM2.5 concentration distribution

Annual energy consumption

According to the relevant Chinese building standard (MOHURD, 2012), the fresh air requirement for residences, hotel rooms, and offices ranges from 0.5 to 1.5 h^{-1}. Figure 2 shows the annual energy consumption simulation results for different indoor PM2.5 concentration control objectives (15 $\mu g/m^3$, 35 $\mu g/m^3$, and 50 $\mu g/m^3$) when the fresh air requirement is 1.0 h^{-1} (i.e. N_{nf} or $N_{mf} = 1.0\ h^{-1}$).

As shown in Figure 2, generally the FAU-Mode consumes less energy than the AP-Mode. The more serious the outdoor PM2.5 pollution is, the more energy-saving the FAU-Mode becomes. Besides, when the indoor target PM2.5 concentration reduces from 50 to 15 $\mu g/m^3$, the annual energy consumption of the AP-Mode increases much more sharply than that of the FAU-Mode.

Considering the three cities, the FAU-Mode is more energy-saving in Beijing under different indoor target PM2.5 concentrations; the lower the indoor target PM2.5 concentration is, the more energy-saving the FAU-Mode can be. Shanghai has the same regularity with Beijing, but when the indoor target PM2.5 concentration is 50 $\mu g/m^3$, the energy consumption difference between the two modes is within 35%. For Guangzhou, when the indoor target PM2.5 concentration is 15 $\mu g/m^3$, the FAU-Mode saves 60% of the energy than the AP-Mode; when the indoor target PM2.5 concentration is 35 or 50 $\mu g/m^3$, the FAU-Mode does not show any energy saving performance.

Similar conclusions can be drawn when the fresh air requirement is 0.5 or 1.5 h^{-1}.

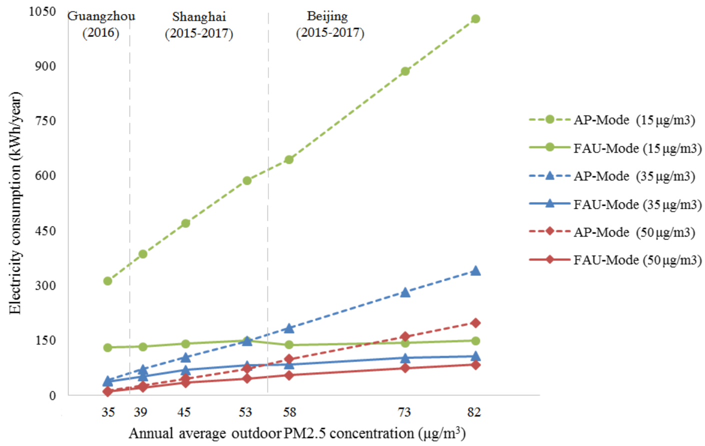

Figure 2: Annual energy consumptions of the two modes (fresh air requirement: 1.0 h^{-1})

Novelty and Conclusion

The annual energy consumptions of the AP-Mode and FAU-Mode are simulated when the two modes are used to supply the same amount of fresh air and reduce the indoor PM2.5 concentration to the same value. Based on the simulation results, optimal air purification strategies for NAC buildings in different cities of China are determined.

It is concluded that when the indoor target PM2.5 concentration ranges from 50 to 15 $\mu g/m^3$, the FAU-Mode is suitable for cities with more serious air pollution, such as Beijing and Shanghai. For Guangzhou, the FAU-Mode should be used when the indoor target PM2.5 concentration is 15 $\mu g/m^3$; for indoor target PM2.5 concentrations of 35 and 50 $\mu g/m^3$, the two modes are both suitable.

References

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