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Influencing factors and energy-saving control strategies for indoor fine particles in commercial office buildings in six Chinese cities

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ABSTRACT

Experimental studies on indoor fine particles were performed in actual commercial offices in six Chinese cities: Beijing, Shanghai, Guangzhou, Tianjin, Shijiazhuang and Chengdu. Particle introduced through outdoor air supply (OA) system was the most significant contributor to indoor $PM_{2.5}$. In most cases, the OA systems of the six office buildings could not provide enough protection for staff. The first reason was the insufficient filtration efficiency of the OA system for $PM_{2.5}$ due to filter bypass and design shortage. The tested filtration efficiency of the OA system for $PM_{2.5}$ ranged from $17.0 \pm 0.9\%$ to $55.7 \pm 2.8\%$. The gaps between the tested and rated filtration efficiencies ranged from 4.4% to 26.3%. The gaps between the rated and required filtration efficiencies ranged from 7.4% to 64.5%. The second reason was the superfluous outdoor air supply rate. The outdoor air supply rates per staff could reach 7.5 L/s to 12.8 L/s with the operating OA systems, much higher than the ASHRAE guideline. Five control strategies (including higher level filters, minimum outdoor air supply rates, portable air cleaners and combinations of these options) were proposed for HVAC system to reduce indoor $PM_{2.5}$ concentration level to 35 $\mu g/m^3$. The reduced indoor $PM_{2.5}$ exposure per power under strategy 2 (minimum outdoor air supply rate + higher level filters) was the highest in all cases. The total energy consumption of HVAC systems under strategy 2 was only 42%-71% of the current energy consumption.

1. Introduction

It is well known that people spend more than 80%–90% of their daily life indoors [1,2]. Especially, many people spend a significant portion of their weekdays in office buildings. Buildings consume approximately 40% of global energy use [3], and air conditioning accounts for 12%–24% of the total energy consumed by well-insulated buildings [4]. However, indoor environment quality (IAQ) is still unsatisfactory in many office buildings. WHO estimated that 30% of new and redecorated offices showed signs of sick building syndrome and that 10–30% of staff were affected [5]. The relationship between particulate matter (PM) concentrations, especially fine particles ($PM_{2.5}$), and adverse health outcomes has been documented in epidemiological studies [6,7].

Several studies focused on the concentration and chemical characterization of $PM_{2.5}$ in office buildings [8,9] and found that the $PM_{2.5}$ mass concentration exceeded the 10 $\mu g/m^3$ recommended by the WHO in many cases [10]. The possible origins of indoor $PM_{2.5}$ are outdoor particles transported indoors – via mechanical ventilation, natural ventilation and penetration – as well as indoor sources of $PM_{2.5}$. In a typical office, outdoor $PM_{2.5}$ was the main source of indoor $PM_{2.5}$ [11,12]. Sangiorgi et al. [12] reported that in office buildings more than 80% of indoor $PM_{2.5}$ was from outdoor sources. Indoor sources, such as the use of laser printers, indeed make a considerable contribution to the indoor ultrafine particles number concentration [13], while they have little effect on indoor $PM_{2.5}$ mass concentration. The movement of people mainly increased the resuspension of particles with diameters larger than 5 μm [14].

Filtration devices in mechanically ventilated office buildings are used to reduce indoor particle exposures [15]. 90% of the indoor air is recirculated and filtered in office buildings in the U.S. and Singapore, [16]. A single zone mathematical model was used to study the influence of air filtration and ventilation on indoor particles in a hypothetical office building [17]. According to this study, the amount of ambient air delivered should be reduced and the filtration level should be increased when outdoor particle concentrations were high. In addition, portable air cleaners are also a good choice to reduce the adverse health influence of indoor exposure to particles [18]. They are easy-to-use in office environments without changing existing layout.

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It should be noted that all above studies were conducted in developed countries with relatively low outdoor $PM_{2.5}$ concentrations. China is one of the most air polluted countries globally. However, less attention was paid to the exposures to $PM_{2.5}$ in Chinese office buildings. Zhu et al. [19] and Mohammed et al. [20] investigated the $PM_{2.5}$-bound PAHs in office buildings in China. Ai and Mak [21] studied the IAQ in naturally ventilated office buildings in China. However, a large portion of Chinese office buildings directly used the outdoor air (OA) system to supply filtered fresh air. This is much different from the recirculated air systems used in developed countries, which should be further studied. In addition, improved control strategies for indoor fine particles in commercial office buildings, such as using high-level filters in filtration systems or portable air cleaners, have not been well explored yet.

In our research, a series of experimental studies was conducted in actual commercial offices in six Chinese cities: Beijing, Shanghai, Guangzhou, Tianjin, Shijiazhuang and Chengdu, located in different climate zones with varied outdoor $PM_{2.5}$ levels. This research mainly concentrated on: (i) the relations between indoor and outdoor fine particles; (ii) the effects of filtration efficiency, outdoor air supply rate and pressure differences on indoor $PM_{2.5}$ concentrations; and (iii) the optimal control strategies to improve IAQ in offices considering both $PM_{2.5}$ concentration reduction and energy consumption of HVAC systems.

2. Methods

2.1. Information about the studied offices

This study was carried out in six important Chinese cities: Beijing (BJ), Tianjin (TJ), Shijiazhuang (SJZ), Shanghai (SH), Guangzhou (GZ) and Chengdu (CD) from July to October 2014, as shown in Fig. 1. All the offices are located in the most developed regions in China, characterized by considerable human activity and dense traffic. The selected office buildings were built upon steel frames, glass curtain walls, and closed windows, which represented typical office buildings in Chinese urban areas. One-year-duration ambient $PM_{2.5}$ mass concentration data were collected by the air quality monitoring station nearest to each office building. Outdoor $PM_{2.5}$ pollution levels (daily average values) are classified at six levels: excellent (0–35 $\mu g/m^3$), fine (35–75 $\mu g/m^3$), slight pollution (75–115 $\mu g/m^3$), medium pollution (115–150 $\mu g/m^3$), serious pollution (150–250 $\mu g/m^3$) and severe pollution (>250 $\mu g/m^3$) according to the classification standard of China's Environmental Monitoring Station. Not surprisingly, the proportions of days when outdoor $PM_{2.5}$ concentrations lower than 35 $\mu g/m^3$ in BJ, TJ, SJZ, SH, GZ and CD were only 26%, 16%, 7%, 25%, 38% and 21%, respectively.

All six office buildings have been in operation for at least five years. During our study, these buildings used centralized outdoor air (OA) systems consisting of several air-handling units (AHUs) to supply fresh air into offices. The outside air was introduced by a supply fan and then filtered by a series of air cleaners, each with a nominal size of 0.6 m by 0.6 m. The filtered air went through the coils for cooling and heating and was finally supplied to the offices through ceiling diffusers. Simultaneous tests of indoor and ambient fine particle concentration were conducted in one office in each building. Offices in different cities were selected to be located on the same floor, with similar areas and numbers of staff. Table 1 lists detailed information on the offices selected. The indoor furnishings mainly included chairs, desks, and desktop computers. No office had printers or copying machines. Photocopying and printing tasks should be performed in separate rooms with exhaust systems. Smoking was also prohibited. The movement of staff in the offices was occasional. Therefore, indoor $PM_{2.5}$ sources were negligible in this study.

2.2. Sampling instrumentation

2.2.1. $PM_{2.5}$ mass concentration

Two portable optical monitoring devices (Dusttrak Model 8530, TSI Inc., St. Paul, MN) were used to measure the indoor and outdoor $PM_{2.5}$ concentrations simultaneously. The indoor sampling sites were located in the middle of the office, at a height of 1.2 m. The particle counter used to measure outdoor $PM_{2.5}$ concentrations was fixed by a support on the external wall at the same height. Indoor and outdoor $PM_{2.5}$ mass concentrations at each site were measured simultaneously for at least two weeks during office hours (from 9:00AM to 17:00PM) at intervals of 5 min. The two particle counters were calibrated using data from the nearest air quality monitoring station; calibration was performed by placing the counters next to the station and comparing the measured $PM_{2.5}$ mass concentrations for at least 5 h before each test. Tapered Element Oscillating Microbalance (TEOM) 1405D (Thermo Environmental Instruments, Franklin, MA) was used in the air quality monitoring station. In addition, the particle concentrations measured by the two devices were basically the same at the same point, with a minimum R^2 value of 0.99 ($p < 0.001$) and a slope value of 1.09.

2.2.2. Filtration efficiency

Two sets of instruments, each including one portable optical monitoring device (Dusttrak, 8530) and one particle counter (Lighthouse Model 2016, Lighthouse Inc., Charlottesville, VA) were used to measure the filtration efficiency of the OA system for $PM_{2.5}$ mass and particle number concentration. One set of instruments was placed upstream of the filters, while the other downstream. The two sets of instruments monitored simultaneously for at least five hours at intervals of 30s. The filter filtration efficiency can be calculated as follows:

$$\eta = \left(1 - \frac{C_d}{C_u}\right) \times 100\% \quad (1)$$

where η is the filtration efficiency for $PM_{2.5}$ mass concentration or particle number concentration; C_d is the $PM_{2.5}$ mass concentration or particle number concentration tested downstream of the filter ($\mu g/m^3$ or pt/cm^3); and C_u is the $PM_{2.5}$ mass concentration or particle number concentration tested upstream of the filter ($\mu g/m^3$ or pt/cm^3). The particle counter (Lighthouse 2016) divided the particles into five channels according to their diameters (0.2–0.3 μm, 0.3–0.5 μm, 0.5–0.7 μm, 0.7–1.0 μm, 1.0–2.0 μm). Therefore, the calculated filtration efficiency was also divided into five categories. The two particle counters were calibrated by the manufacturer and were inter-compared before each test.

2.2.3. Air exchange rate and pressure difference

When the OA system was turned on, the air exchange rate could be calculated by the tested outdoor airflow rate and office volume:

$$ach_{on} = \frac{Q_{OA}}{V} \quad (2)$$

where ach_{on} is the outdoor air exchange rate when the OA system was on (h^{-1}); Q_{OA} is the supply volume of the OA system (m^3/h); and V is the volume of the office (m^3). The supply volume of the OA system was calculated according to the air velocity tested at the air supply outlet by a multi-parameter ventilation meter (Model 8386, TSI Inc., St. Paul, MN). When the OA system was turned off, the outdoor air exchange rate for each office could be obtained by the indoor CO_2 decay method. The decay tests were conducted after work hours with the OA system shut down and windows closed.

Five non-dispersive infrared (NDIR) CO_2 meters (Model K-33 ELG, CO_2 Meter, Inc.) were located indoors at a height of 1.2 m to measure the indoor CO_2 concentration simultaneously at 5-min intervals. One CO_2 meter was located at the center of the office,