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Analysis of the impact of a fresh air system on the indoor environment in office buildings

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ABSTRACT

This study conducted objective physical tests and subjective questionnaire surveys related to the operation of a fresh air system in an office building in Beijing before the outbreak of the coronavirus disease 2019 (COVID-19). The long-term tests on indoor environmental parameters included air temperature, relative air humidity, air velocity, CO\textsubscript{2} concentration, PM\textsubscript{2.5} concentration, and fresh air volume, and the questionnaire surveyed the satisfaction of office workers in the indoor environment. The results showed that the indoor environmental parameters conformed to the values specified in relevant design standards; however, the satisfaction with the indoor environmental parameters was generally low. The probability of infection of indoor personnel with the virus causing COVID-19 under two existing fresh air system operation modes was calculated and compared, and it was less than 5%. A gray correlation analysis of the measured data with the questionnaire results identified indoor air temperature and quality as the main factors affecting the subjective satisfaction, which was consistent with the results of the questionnaire analysis. A new operation and maintenance method for fresh air systems was proposed for regular epidemic prevention and control to ensure the normal operation of the office building and the health of indoor personnel.

1. Introduction

Architecture provides a healthy and comfortable environment for people in the places where they live and work. More than 90% of people spend their time indoors. Many studies have pointed out that the quality of the indoor environment has an important impact on the comfort, health, and productivity of indoor personnel (Asadi, Mahyuddin & Shafigh, 2017; Geng, Ji, Lin & Zhu, 2017; Vilcekova et al., 2017). With the rapid development of China’s economy, urbanization is accelerating, and living standards have continued to improve in the northern region. At the same time, in recent years, frequent haze pollution and long-term exposure to the polluted environment are seriously affecting the health of personnel. The coronavirus disease 2019 (COVID-19) broke out at the end of 2019 and spread rapidly across the globe, posing a huge threat to the lives and health of people worldwide. The virus is highly transmissible from person to person and is significantly more infectious than SARS-CoV and MERS-CoV (Wang C & Hayden, 2020; Yan et al., 2021). At present, it is generally believed that COVID-19 can be transmitted through contact, droplets, and aerosols in relatively confined environments with high concentrations of aerosols, and health problems caused by the building indoor environment have gradually become the focus of attention.

Table 1 showed the research overview of building indoor environment comfort and personnel satisfaction.

The indoor environment of a building is affected by a combination of thermal, acoustic, light, and indoor air quality factors (Lou & Ou, 2019; Zuhaib et al., 2018). Many scholars have conducted objective and long-term measurement of indoor environmental parameters and thoroughly analyzed the indoor environmental quality of office buildings (Al Horr et al., 2016; Choi, Loftness & Aziz, 2012; Tham, Wargocki & Yan, 2015).

(Al Horr et al., 2016) took an objective approach to office buildings by testing indoor air quality and ventilation, thermal comfort, lighting and daylighting, noise and acoustics, office layout, biophilia and views, look and feel, location and amenities were objectively tested to analyze the current state of the environment in office buildings.

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the choice of building indoor temperature and humidity, (Geng et al., 2019) also uses carbon dioxide concentration and PM2.5 concentration as important indicators to evaluate the building indoor environment in different climatic regions of China. In addition to the indoor environment of office buildings, some scholars also studied the indoor environment of residential buildings and apartments (Huang, Sun, Feng, Wang & Song, 2020; Sharmin et al., 2014; Zhao, Liu & Ren, 2018). (Zhao et al., 2018) used a combined wireless network air quality sensor to conduct long-term testing of indoor PM₂.₅ concentrations in residential buildings under three different ventilation modes. (Huang et al., 2020) investigated the improvement in indoor air quality in residential buildings using fresh air systems by collecting data on indoor temperature and concentrations of formaldehyde, VOCs, CO₂, and PM₂.₅. The results showed that fresh air systems can significantly reduce PM₂.₅ concentrations and improve air quality. (Sharmin et al., 2014) monitored the energy systems and indoor air quality of a building and analyzed the factors affecting indoor air quality, as well as the comfort of the occupants. 

Subjective analysis is also an important method to explore the indoor environment. Questionnaires are mainly used to obtain the subjective perceptions and satisfaction of people in the building regarding the environment. (Zhang, 2019) conducted a questionnaire survey considering four aspects of a university library building, namely, interior design, indoor environment, performance, and user satisfaction, and then established a structural equation model based on the theory of evaluation. In a case study of green and traditional office buildings in Brazil, Sant’ Ana, Santos, Vianna & Romero, 2018) conducted a questionnaire survey with the interior staff and visitors of the buildings and analyzed the objective indoor environment and interior staff’s feelings and satisfaction for different building types. Agha-Hossein, El-Jouzi, Elmulim, Ellis and Williams (2013) conducted a questionnaire on the subjective satisfaction of indoor environment with personnel in new and old office buildings. According to the results, new buildings consume less energy and an enhancement in the indoor personnel’s regulation of the indoor environment will not reduce their satisfaction with the environment and can effectively reduce the energy consumption of the air conditioning system. (Liu, Wang, Lin, Hong & Zhu, 2018) applied a questionnaire survey method to investigate the satisfaction of indoor personnel, focusing on a comparative analysis of the environmental impact on the indoor personnel of three-star green office buildings in China and office buildings based on the LEED or BREEAM certification.

The comprehensive assessment method combines objective and subjective analysis, and analyses the indoor environment by blending the two to establish interrelationships. (Liu & Ou, 2019) conducted physical measurements of the indoor environment and subjective evaluations of staff satisfaction in open administrative offices and open research laboratories on university campuses, comparing four aspects: indoor thermal environment, acoustic environment, light environment, and air quality. (Cao et al., 2012) performed actual measurements of the indoor environment of public buildings in Beijing and Shanghai and investigated the subjective satisfaction of indoor personnel. Based on this, a regression model of the indoor environmental parameters and personnel satisfaction was established to make overall predictions and assessments of the indoor environment. (Pei, Lin, Liu & Zhu, 2015) selected thermal environment, indoor air quality, visual and acoustic environment as the evaluation indicators, and combination of subjective and objective methods to study green and traditional office buildings in two different climatic regions in China. (Andargie & Azar, 2019) developed an integrated data collection and analysis framework to comprehensively evaluate the impact of the built environment in offices on occupant comfort, satisfaction and work performance.

Based on the above studies, many scholars have conducted a substantial amount of research on the indoor environment from objective

### Table 1
An overview of the research on building indoor environment comfort and personnel satisfaction.

| Evaluation Methods | Subjects of study | Indicators | Data Acquisition | Reference |
|--------------------|-------------------|------------|------------------|-----------|
| Objective          | Office building   | Indoor Air Quality and Ventilation, Thermal Comfort, Lighting and Daylighting, Noise and Acoustics, Office Layout, Biophilia and Views, Look and Feel, Location and Amenities | Physical measurements | (Al Horr et al., 2016) |
|                    | Green office building | Air temperature, Relative humidity, CO₂, PM₂.₅, Illuminance | Long-term measurement | (Geng et al., 2019) |
|                    | Dwellings | CO₂, PM₂.₅, Energy consumption | Long-term monitoring | (Zhao et al., 2018) |
|                    | Residential buildings | Temperature and concentrations of Formaldehyde, VOC, CO₂, and PM₂.₅ | Long-term monitoring | (Huang et al., 2020) |
|                    | Apartment | Energy consumption, CO₂ concentration, Relative humidity | Physical measurements | (Sharmin et al., 2014) |
| Subjective         | University libraries | Interior design, Indoor environment quality | Face-to-face interviews | (Geng et al., 2019) |
|                    | Conventional and green buildings | Thermal comfort, Lighting, Acoustics, Ergonomics, Cleaning, Air quality | Semi-enclosed questionnaires | (Zhao et al., 2018) |
|                    | Office building | Indoor environment quality | Questionnaires | (Agha-Hossein et al., 2013) |
|                    | Three-Star certified and non-certified office buildings | Air freshness, Air cleanliness, Humidity, Natural lighting, Acoustic environment, Colors & Textures, IEQ control, Building cleanliness, Building maintenance | Questionnaires | (Liu et al., 2018) |
| Objective & Subjective | University building | Air temperature, Relative humidity, Mean radiant temperature, Air velocity, Illumination, CO₂ and Noise level | Physical & Subjective measurements | (Zuhaib et al., 2018) |
|                    | Office building | Layout, Air quality, Thermal comfort, Lighting and Acoustic environment | Physical & Questionnaires | (Liu & Ou, 2019) |
|                    | Office building | Thermal, Air quality, Lighting/Visual, and Acoustic measurements | Environmental measurements/Satisfaction Questionnaires | (Choi et al., 2012) |
|                    | Public buildings | Air temperature, Mean radiant temperature, Relative humidity, Air velocity, CO₂, Illumination intensity, Sound pressure levels | Physical & Questionnaires measurements | (Cao et al., 2012) |
|                    | Green office buildings | Thermal environment, Indoor air quality, Visual and Acoustic environment | Objective & Subjective measurements | (Pei et al., 2015) |
|                    | University office buildings | Sound level, Air velocity, Radiant temperature, Air temperature, Illuminance, Relative humidity | Objective & Subjective measurements | (Andargie & Azar, 2019) |
and subjective aspects including thermal environment, air quality, acoustic environment, and light environment. However, there are relatively few studies on the influence of fresh air systems on indoor environments. Many studies (Chan, Yuan & Kok, 2020; General Office of National Health Commission, Office of State Administration of Traditional Chinese Medicine, 2020; Paules, Marston & Fauci, 2020) have pointed out that the mechanical ventilation of fresh air systems plays an important role as it can dilute harmful substances and filter dust and bacteria, thus improving the indoor environment and ensuring the health of indoor personnel (ASHRAE, 2017; Engvall, Wickman & Norback, 2005; Liu, Gong & Lian, 2000).

In this study, through actual testing of indoor environmental parameters (air temperature, relative humidity, CO₂ concentration, PM₂.₅, indoor air velocity, and fresh air volume) in an office building in Beijing during the summer before the COVID-19 outbreak, the fresh air system operation was investigated. Indoor environmental satisfaction questionnaires were administered to indoor office personnel during the testing period.

The results were statistically analyzed using SPSS, and the influence of indoor environment parameters on the satisfaction of personnel was analyzed using the gray correlation method. According to the existing fresh air system operation mode, the probability of virus infection for indoor personnel was calculated. The problems and shortcomings in the operation of the existing fresh air system and the development of regular epidemic prevention and control measures were considered. To ensure the normal operation of the office building and health of the occupants, operation management methods and suggestions for the fresh air system operation were proposed. This study provides a theoretical basis for improving the indoor environment and enhancing the operational efficiency of fresh air systems.

2. Methods

2.1. Research framework

Fig. 1 shows the research framework of office building fresh air system. This study focused on the impact of fresh air systems in office buildings on indoor environment and personnel satisfaction. Firstly, determine the office building fresh air system and indoor environment as the main content and object. Then, the impact of fresh air system on indoor environment and personnel satisfaction was analyzed from objective and subjective perspectives. On the one hand, from an objective point of view, the indoor environment parameter during the operation of the fresh air system is mainly tested by environmental monitoring device. On the other hand, from a subjective point of view, questionnaires are mainly used to investigate the basic information of the staff in office buildings, their satisfaction with the indoor environment and their physical comfort. Finally, this study adopts gray correlation analysis method to analyze the measured data and questionnaire results, and explores the main factors affecting the personnel satisfaction when the fresh air system is operating in office buildings.

2.2. Case study

This study focused on indoor environmental parameters such as Temperature, Relative humidity, CO₂ concentration, PM₂.₅, Air velocity, and Fresh air volume in an office building in Beijing during summer operation of the fresh air system. The influence of the fresh air system on the indoor environment was analyzed through long-term practical monitoring. An office building in Beijing was selected as the research object in this study. The air conditioning system consisted of a fan coil and a fresh air system. Table 2 presents the basic information about the office.

Table 2

| Room size (m²) | Room height (m) | People | Air conditioning / Fresh air system | Work time |
|---------------|-----------------|--------|-------------------------------------|-----------|
| 30–50         | 2.5             | 2-4    | Yes                                 | 9:00–18:00|

Fig. 2 shows the indoor measuring points and fresh air system layout of the office building. The triangles, circular and squares represent the installation positions of the environmental detection devices, fresh air outlets, and return air outlets, respectively.

2.3. Indoor environmental parameter monitoring device

The test apparatus used in this study is shown in Fig. 3 and Fig. 4. In this study, the IBEM integrated environmental monitoring device can continuously and accurately detect indoor environmental parameters and record the data in an SD card in the device. The IBEM indoor environmental parameter monitoring device contains temperature, relative humidity, CO₂ concentration, and PM₂.₅ concentration detection modules (China Indoor Environment Test Center, 2011; General Administration of Quality Supervision, 2005; General Administration of...
Quality Supervision, 2014; General Administration of Quality Supervision, 2012; General Administration of Quality Supervision, 2001). The indoor environment detection was realized through a two-month long-term test in August and September. The detection data recording interval was set to 5 min and the indoor environment of the building was tested during 24 h. A Testo 405i anemometer was used to detect the indoor air velocity, and the fresh air volume was calculated by the anemometer. Table 3 lists detailed information on the IBEM indoor environmental parameter monitoring equipment and the Testo anemometer.

2.4. Subjective survey of satisfaction with the indoor environment

To investigate the satisfaction of the personnel with the indoor environment, a questionnaire survey method was adopted. The respondents answered questions about the indoor environment, and a statistical analysis was conducted on the results of the questionnaire to obtain the subjective feelings of the occupants about this environment.

Questionnaire analysis methods mainly include face-to-face and online questionnaire surveys. Considering that the staff in an office are relatively busy and a network questionnaire has the characteristics of easy dissemination and collection, this study adopted the network questionnaire survey method. Thus, a network electronic questionnaire was issued to the indoor staff of the office building. The questionnaire mainly included three parts: 1) basic information of the surveyed person, such as gender, age, type of work, daily working hours, physical health status, and clothing worn when filling out the questionnaire; 2) satisfaction of the surveyed person with the indoor temperature, relative humidity, air quality, and indoor air velocity in the building; and 3) whether the respondent feels physical discomfort in the building’s interior and satisfaction with the overall indoor environment when completing the questionnaire. The questionnaire used a five-point Likert scale to measure the satisfaction and physical condition of indoor personnel in the office building during operation of the fresh air system. Satisfaction was measured based on the size of the score (Zhang, 2019).

Three normal working days were selected to distribute questionnaires and conduct actual surveys on the satisfaction of the indoor environment personnel. Each day, more than 30 questionnaires were issued. In total, 115 questionnaires were returned and 105 questionnaires were valid, including 56 from male and 49 from female respondents, for a questionnaire recovery rate of 91.5%. SPSS version 24.0 was adopted to analyze the questionnaire data, using the Cronbach’s coefficient to test the consistency of the questionnaire. The partial correlation Bartlett test and Kaiser–Meyer–Olkin (KMO) test were applied to determine the effectiveness of the questionnaire. The Pearson correlation coefficient was used to analyze the correlation between factors and the overall satisfaction of the indoor environment personnel.

3. Results and analysis

3.1. Physical measurement results

The thermal comfort level and related parameter design standards for buildings under summer cooling conditions specified in the Design Code for Heating, Ventilation, and Air Conditioning of Civil Buildings (GB 50,736–2012) are listed in Table 4 (ANSI/ASHRAE 55–2010, 2010; Ministry of Housing Urban & Rural Development, 2012). In the subsequent actual detection of indoor temperature in the office building, an
objective evaluation of this temperature was conducted in relation to the recommended values of the standard. As the normal working hours in office buildings are from 9:00 to 18:00, the data for August and September were screened, and daily data samples from 9:00 to 18:00 were retained for analysis and research. In this study, box plotting was used to present and analyze the test data. Boxplots have the advantage of displaying the median value and overall distribution of data in an intuitive manner. The median value is used to represent the overall indoor environment of the building. At the same time, abnormal values in the data batch can be identified, and the hot and humid environment and air quality in the building can be analyzed in those areas where abnormal values appear.

3.1.1. Thermal environment

Indoor air temperature is an important index for evaluating the indoor thermal environment. In a theoretical analysis of the human thermal balance, Fanger considered indoor air temperature as an important factor affecting the thermal comfort of the human body. The human body temperature is a dynamically changing process. The human body maintains the balance and stability of the body temperature through convection and radiant heat exchange with the surrounding air. The indoor air temperature of a building has a direct impact on the heat production and dissipation of the human body.

Fig. 5 shows a box diagram of the actual measured temperature of each indoor measurement point of the studied office building in Beijing under operation of the fresh air system during the summer test. Comparing the test results in the box chart with the standard requirements, the actual measured temperature values at each measurement point varied in a range from 23 °C to 28 °C, which meets the design requirements of indoor air-related standards for air conditioning systems. The difference between the median values of the indoor air temperature at different measuring points was 3.2 °C. According to the results shown in the box diagram, the indoor air temperatures measured at the measurement points of the office buildings under the same air conditioning system were not significantly different. Indoor air temperature has an important impact on the comfort and work efficiency of indoor personnel. From the analysis in Fig. 5 and Fig. 6, the indoor air temperature in the test room was maintained at a high level of comfort during the summer.

Fig. 6 shows the percentage distribution of the measured air temperature at different measurement points.

Fig. 6 shows the percentage distribution of the measured air temperature at different measurement points of office buildings in the summer. The distribution of the measured indoor air temperature at each measurement point showed a larger proportion in the ranges of 24–26 °C and 26–28 °C, with approximately 60% of the data collected at each measurement point. Some points had extremely abnormal values in the measured temperature. The main reason is that the temperature of the indoor air conditioning and the change in the density of indoor personnel caused overheating. Based on the above analysis, combined with the summer indoor air temperature analysis charts shown in Fig. 5 and Fig. 6, it can be observed that the indoor air temperature fluctuations of different rooms in the summer are small and meet the design requirements. The indoor air temperature can be distributed in a more comfortable temperature range to ensure the comfort and health of the indoor office staff.

The relative humidity of indoor air affects the thermal comfort of the human body by affecting the heat dissipation of the human skin and surrounding environment; therefore, the comfort of indoor personnel is affected by the relative humidity of the indoor air. The recommended relative humidity of indoor air in the ASHRAE standard is 40%–60% (ANSI/ASHRAE 55–2010, 2010). When the relative humidity of indoor air changes within the range of 30%–70%, there is no significant effect on the comfort of indoor personnel. If the indoor environment is in a high-temperature and high-humidity environment in summer, the indoor humidity will easily breed mold, which will pollute the air and affect the health of indoor personnel. If the relative humidity of indoor air is too low, it will generate indoor dust and excessive suspended particles, which will cause respiratory diseases in the occupants, especially children.

The statistical results for the indoor relative humidity in the office during the summer test are shown in Fig. 7. A comparison of the test results in the box chart with the standard requirements indicates that the relative humidity of the indoor air at each measurement point remains between 30% and 70%, and the average relative humidity of the indoor air at each measurement point fluctuates between 35% and 45%.

From the distribution percentages of the measured values of air relative humidity at different measurement points shown in Fig. 8, the
indoor air relative humidity values at each measurement point were distributed in the 30%–40% and 40%–60% intervals. In measurement points 01 and 11 there was a major proportion in the 30%–40% range. From the overall data, the measured summer indoor air relative humidity in the office was distributed within the recommended range of relative humidity. This test showed that the summer indoor air relative humidity meets the design and human comfort requirements.

### 3.1.2. CO₂ concentration

Scientific research shows that the normal human body consumes 10–13 m³ of air every day to maintain various functions of the body. Air quality is closely related to the life, work, and health of a person. Because the concentration of CO₂ is relatively easy to detect compared to other indoor air pollutants, CO₂ concentration was selected as an important indicator for evaluating the indoor air quality.

Fig. 9 shows the box statistics of the measured indoor CO₂ concentrations in the summer at various measurement points of the office. Regarding the recommended reference values for indoor CO₂ concentration in office buildings presented in Table 4, the median indoor CO₂ concentration in the tested office was consistently lower than 700 ppm when fresh air was continuously sent indoors.

Fig. 10 shows the percentage distribution of the indoor measured CO₂ concentrations at different measurement points. As can be observed, the measured CO₂ concentrations at different measurement points were distributed in the ranges of 400–600 and 600–800 ppm. According to China’s indoor air quality standards, the indoor CO₂ concentration should not exceed 1000 ppm. It can be known that during the operation of the fresh air system in the test office building in summer, the indoor CO₂ concentration was controlled below 1000 ppm. It was also found that the CO₂ concentration exceeding the standard was greatly affected by the change in indoor personnel density (GB/T1883-2002, 2003). In addition, during operation of the air conditioning system, the maintenance department faced problems such as shortening the opening time of the fresh air system to reduce the operating energy consumption.

### 3.1.3. PMₐ₂·₅ concentration

The PMₐ₂·₅ pollution sources in office buildings are mainly divided into indoor and outdoor sources. Indoor pollution sources include harmful gasses and particulates released by office staff and photocopying equipment. The outdoor pollution sources include soil dust, motor vehicle exhaust, coal combustion, and chemical pollution. In industrial emissions of gas, for example, bring PMₐ₂·₅ into the building’s interior through the doors and windows of the building, natural ventilation, air conditioning, and fresh air systems. PMₐ₂·₅ is composed of a variety of chemical components with an equivalent diameter of 2.5 μm or less. Harmful substances, such as bacteria and viruses, are easily attached to the surface of particulate matter, and various diseases of the human body are induced by air transmission. Therefore, the fresh air system plays an important role in reducing the indoor PMₐ₂·₅ concentration and ensuring the health of indoor personnel.

Fig. 11 shows the statistical results of the PMₐ₂·₅ concentration at
Fig. 11. PM$_{2.5}$ concentration at each indoor measurement point in summer.

Fig. 12. Percentage distribution of PM$_{2.5}$ concentration at different measurement points.

Fig. 13. Line graph of change in indoor air velocity for three working days during the test period.

various measuring points in the office in summer. According to China’s current "Indoor Air Quality Standards" and related regulations, indoor PM$_{2.5}$ concentration should not exceed 35 µg/m$^3$. Comparing this value with the test results in the box chart, we can observe that the current situation of indoor PM$_{2.5}$ concentration in the test office is not satisfactory because the measured concentration value exceeds the standard value of 35 µg/m$^3$ (GB/T1883-2002, 2003). The PM$_{2.5}$ concentration at measurement points 02, 03, 04, 12, 13, and 14 showed many local outliers exceeding the standard in some periods. According to the regulations of indoor air PM$_{2.5}$ stipulated by the World Health Organization Air Quality Guidelines, within 24 h the concentration of PM$_{2.5}$ should not exceed 75 µg/m$^3$. The median PM$_{2.5}$ concentration at each measurement point was less than 75 µg/m$^3$ (WHO, 2005).

Combining the measured percentage distribution of indoor PM$_{2.5}$ concentration at different measurement points shown in Fig. 12, it can be observed that the indoor PM$_{2.5}$ concentration meets the relevant requirements of the standard as it does not exceed 75 µg/m$^3$.

In relation to the indoor PM$_{2.5}$ concentration values that exceed the standard, through the actual investigation it was found that the indoor PM$_{2.5}$ concentration is closely related to the outdoor environmental quality. In addition, indoor personnel move between indoors and outdoors, and PM$_{2.5}$ will be adsorbed on their clothing and brought into the room. Further, through the actual investigation, it was found that the presence of printers and other office equipment and incomplete filtering of the fresh air system were the main reasons for the indoor PM$_{2.5}$ concentration values being seriously exceeded.

3.1.4. Air velocity

The indoor air velocity was measured using a Testo anemometer, and Fig. 13 shows a line graph of the change in indoor air velocity in the office during a randomly selected test period of three working days. Combined with Table 4, the indoor air velocity in the office was less than or equal to 0.3 m/s to meet the design requirements of indoor air velocity in office buildings. All the office buildings tested used fan coils and fresh air systems to regulate the indoor environment, and the indoor air conditioning panel parameters were set the same in summer. During the test period, the indoor air velocity of an office from 9:00 to 18:00 on a normal working day was selected for testing. As shown in Fig. 13, the indoor air velocity in the office during each normal working day meets the Class I and Class II design requirements for indoor air velocity under the cooling conditions of the Design Code for Heating, Ventilation, and Air Conditioning of Civil Buildings.

3.1.5. Fresh air volume

In this study, we measured the indoor fresh air volume in this office building with respect to the measurement parameters of indoor ambient air quality and provided a reference for improving the indoor air quality. The indoor CO$_2$ concentration is an important index used to characterize the amount of fresh air, and the standard GB/T 18,883–2002 stipulates that the indoor fresh air per capita should not be less than 30 m$^3$/h, and the indoor CO$_2$ concentration should not exceed 1000 ppm.

When there is no CO$_2$ emitting source in the room, the formula for calculating the fresh indoor air volume is shown in Eq. (1):

$$\ln(C - C_{\text{out}}) = \ln(C_0 - C_{\text{out}}) - At \tag{1}$$

At that time, there was a stable source of CO$_2$ dispersion in the building. Because the indoor personnel of the building were the main source of CO$_2$ dispersion, the indoor fresh air volume was calculated according to the environmental quality balance equation, as shown in Eq. (2):

$$\ln(C - C_{\text{out}} - Q_0/q) = \ln(C_0 - C_{\text{out}} - Q_0/q) - At \tag{2}$$

Based on the measured indoor CO$_2$ concentrations, the fresh indoor air volume was calculated using the difference method. The calculation accuracy of the difference method is closely related to the indoor CO$_2$ dispersion rate and the divided time interval: the smaller the time interval is, the more the change tends to be transient and more accurate (Li-xin, Yu-hua, Zhao-rong & Jin-long, 2007), as shown in Eq. (3):

$$\ln(C - C_{\text{out}} - Q_0/q) = \ln(C_0 - C_{\text{out}} - Q_0/q) - At \tag{3}$$
Fig. 14. Line graph of the change in indoor CO2 concentration for full-time and part-time fresh air operation.

Table 5 Calculation results of indoor fresh air volume based on the difference method.

| Operating hours | Area per capita (m²) | Space (m²) (Floor height 2.5 m) | CO2 concentration fluctuation range | Fresh air volume per capita (m³/h) |
|-----------------|---------------------|---------------------------------|-----------------------------------|-------------------------------|
| Full time       | 12.5                | 125                             | 600–700 ppm                       | 40.5                          |
| Part time       | 12.5                | 125                             | 600–800 ppm                       | 35.7                          |
| Full time       | 12.5                | 125                             | 800–1000 ppm                      | 26.5                          |
| Part time       | 12.5                | 125                             | 700–1000 ppm                      | 28                            |

Table 6 Probability of infection of healthy persons.

| Operation mode | Daily per capita fresh air volume (m³/h) | Dilution times | Probability of infection (Pₚ) |
|----------------|----------------------------------------|----------------|---------------------------|
| Full-time      | 33.5                                   | 112            | 2.8%                      |
| Part-time      | 31.8                                   | 106            | 4.9%                      |

The calculation shows that the probability of infection for indoor personnel in this office building is 2.8% and 4.9% for the full-time and part-time modes of operation, respectively.Because of the extremely high pathogenicity of the new coronavirus, it is important to protect against it and not ignore the infectiousness of this virus.
of 1000 ppm, the required fresh air volume was 30 m$^3$/h. According to the results of the difference method, when the CO$_2$ concentration is maintained at 600–700 ppm, the required fresh air volume per person is 40.5 m$^3$/h, which is higher than the standard of 30 m$^3$/h.

At present, owing to the outbreak of new coronavirus infectious diseases, public buildings are adopting ventilation systems with cleaning and disinfection, increasing the amount of fresh air and all fresh air operations to ensure the indoor environment. Comparing the fresh air volume calculated with the difference method and the actual measurement results, it can be observed that a fresh air volume per capita of 30 m$^3$/h can ensure that the indoor CO$_2$ concentration in office buildings does not exceed 1000 ppm (Dayue & Jinyan, 2007). If the indoor CO$_2$ concentration is maintained at 600–700 ppm or even lower, the fresh air volume per capita will be higher than the standard of 30 m$^3$/h. The increase in fresh air volume will lead to a significant increase in energy consumption for the system. However, in the current serious epidemic situation, increasing the fresh air volume is the most effective way to ensure the health of indoor personnel.

### 3.2. Subjective evaluation result

#### 3.2.1. Questionnaire reliability and validity analysis

Cronbach’s coefficient was used to test the reliability of the collected questionnaires, and the Bartlett spherical and KMO tests were used to determine the validity of the questionnaires. Analysis of the collected questionnaire data showed that Cronbach’s coefficient was 0.828 and the KMO value was 0.841. According to several studies, when the Cronbach’s coefficient and KMO value are in the range of 0.8–0.9, the results of the questionnaire are consistent and reliable, and thus considered valid (Miller, 1995; Tavakol & Dennick, 2011).

#### 3.2.2. Satisfaction analysis of indoor environmental parameters

As presented in Table 7, the overall satisfaction of indoor personnel based on the subjective feelings toward the indoor environment was 3.69, followed by indoor air quality with 3.66, indoor air temperature with 3.61, fresh air volume with 3.59, indoor air velocity with 3.32, and indoor air relative humidity with 3.51. The average satisfaction rate of office workers for indoor odors was 3.30. Therefore, it can be observed that during operation of the investigated summer fresh air system in the office building, the overall satisfaction based on the subjective feelings of the indoor personnel was the highest, and the personnel had the highest satisfaction with the indoor air temperature and air quality. Consequently, according to the research on fresh air systems in office buildings during the summer, indoor workers have subjective feelings of overall satisfaction, and the degree of satisfaction is higher for the indoor air quality and air temperature. However, the average satisfaction based on subjective feelings was closer to a neutral value rather than to a very satisfactory value of 5. Therefore, the indoor environment of buildings still needs to be improved, and the subjective satisfaction of indoor environment personnel is relatively poor.

In this study, Spearman’s correlation analysis was performed on various parameters of the indoor environment and the overall satisfaction based on the subjective feelings of indoor environment personnel. The Spearman correlation statistics for the overall satisfaction of indoor environment personnel and the factors affecting the indoor environment are presented in Table 8. The larger the absolute value of the correlation coefficient, the stronger is the correlation between the variables. The maximum correlation coefficient was that between indoor air temperature and indoor environmental satisfaction, 0.701, followed by those of indoor air quality (0.621), indoor air relative humidity (0.538), indoor air velocity (0.417), fresh air volume (0.381), and odor (0.431). The main factors affecting the satisfaction of the personnel with the indoor environment were ranked in descending order according to the correlation values: indoor air temperature, indoor air quality, indoor air relative humidity, odor, indoor air velocity, and fresh air volume.

This shows that the environmental parameters of indoor air temperature and indoor air quality have a greater impact on indoor staff satisfaction than the other ones. According to the comparison and analysis of the average satisfaction score based on the subjective feelings of indoor personnel in Table 7, it can be known that the indoor personnel of the office building under investigation have a high degree of attention to indoor air temperature and indoor air quality. In addition, environmental parameters such as indoor air relative humidity, indoor air velocity, fresh air volume, and odor affect the satisfaction of indoor personnel with their environment and cannot be ignored. Therefore, the design of air conditioning and fresh air systems in office buildings should fully consider the close relationship between various environmental parameters and personnel satisfaction. On the premise of meeting the design requirements, the satisfaction of indoor personnel with their environment should be increased as much as possible to create a healthy and comfortable indoor environment.

### 3.2.3. Grey relational analysis on subjective satisfaction of indoor environment personnel

Since the 1960s, ideas and methods for uncertainty research have been proposed. Professor L. A. Zadeh proposed the fuzzy mathematical theory in 1965, and Professor Deng Julong of China proposed the gray system theory in 1982. These results have had a profound impact on the systematic research on uncertainty at different levels. The gray system theory provides effective solutions and new ideas for solving small data, uncertainty, and poor information problems. Through the analysis of known data, effective information is extracted to identify the change law of system behavior and achieve the expression and control of the system (Deng, 1992; Zhu, Li, & Gai, 2005).

Table 7: Average satisfaction from subjective feelings of indoor personnel.

| Parameter          | Average satisfaction |
|--------------------|----------------------|
| Air temperature    | 3.61                 |
| Relative humidity  | 3.51                 |
| Air velocity       | 3.32                 |
| Air quality        | 3.66                 |
| Fresh air volume   | 3.59                 |
| Odor               | 3.30                 |
| Overall satisfaction| 3.69                 |

Three normal working days were selected during the test, and the indoor staff satisfaction values for the indoor environment were designated as $y(1) = 3.61$, $y(2) = 3.51$, $y(3) = 3.32$, $y(4) = 3.66$, $y(5) = 3.59$, $y(6) = 3.30$, which constitute the reference sequence listed in Table 9.
Table 8
Spearman correlation statistics of indoor environment personnel satisfaction and influencing factors of indoor environment.

| Parameter             | Satisfaction | Air temperature | Relative humidity | Air quality | Air velocity | Fresh air volume | Odor |
|-----------------------|--------------|-----------------|-------------------|------------|-------------|------------------|------|
|                       | 0.701**      | 0.538**         | 0.621**           | 0.417**    | 0.381**     | 0.431**          |      |

Note: **Significant correlation level is 0.01 (both sides).

Table 9
Raw data table for comparison and reference sequences.

| Y  | 0.85 | 0.90 | 0.95 |
|----|------|------|------|
| X1 | 27.2 | 25.4 | 26.7 |
| X2 | 45.5 | 37.3 | 56.5 |
| X3 | 547  | 662  | 685  |
| X4 | 45   | 31   | 89   |
| X5 | 0.21 | 0.29 | 0.27 |
| X6 | 28   | 31   | 27   |

Table 10
Initial image values after raw data pre-processing.

| Y' | 1    | 1.059 | 1.118 |
|----|------|-------|-------|
| X1 | 1    | 0.934 | 0.982 |
| X2 | 1    | 0.819 | 1.242 |
| X3 | 1    | 1.210 | 1.252 |
| X4 | 1    | 0.689 | 1.978 |
| X5 | 1    | 1.381 | 1.285 |
| X6 | 1    | 1.107 | 0.964 |

Table 11
Reference sequence and comparison sequence absolute interpolation table.

| ∆1 | 0    | 0.125 | 0.136 |
|----|------|-------|-------|
| ∆2 | 0    | 0.240 | 0.124 |
| ∆3 | 0    | 0.151 | 0.134 |
| ∆4 | 0    | 0.370 | 0.860 |
| ∆5 | 0    | 0.322 | 0.167 |
| ∆6 | 0    | 0.048 | 0.154 |

Table 12
Correlation coefficient between indoor environment parameters and satisfaction of indoor environment personnel.

| γ1 | γ2 | γ3 | γ4 | γ5 | γ6 |
|----|----|----|----|----|----|
| 1  | 0.775 | 0.642 | 0.740 | 0.538 | 0.572 |
| 1  | 1    | 0.642 | 0.740 | 0.538 | 0.572 |
| 1  | 0.775 | 0.642 | 0.740 | 0.538 | 0.572 |
| 1  | 0.775 | 0.642 | 0.740 | 0.538 | 0.572 |
| 1  | 0.775 | 0.642 | 0.740 | 0.538 | 0.572 |
| 1  | 0.775 | 0.642 | 0.740 | 0.538 | 0.572 |

Table 13
Gray correlation between indoor environment parameters and indoor staff satisfaction.

| Parameter              | 0.924 | 0.806 | 0.834 | 0.623 | 0.764 | 0.878 |
|------------------------|-------|-------|-------|-------|-------|-------|

According to the gray correlation analysis method, Y denotes the reference series and X denotes the comparison series.

The absolute value sequence of the differences between the corresponding components was found. This is the first difference between the reference and comparison sequences, as shown in Eq. (6):

$$
\Delta_i(k) = |Y_i(k) - X_i(k) |
$$

(2) The maximum and minimum differences were found, as shown in Eq. (7):

$$
M = \max_{i,k} \Delta_i(k) = 0.860 \quad m = \min_{i,k} \Delta_i(k) = 0
$$

M is the maximum range and m is the minimum range. When calculating the maximum range, Δi(k) is the value with the largest absolute difference between the comparison sequence and reference sequence, and when calculating the minimum range, Δi(k) is the value with the smallest absolute value of the difference between the comparison and reference sequences.

(3) The correlation coefficient was found, as shown in Eq. (8):

$$
\gamma_i(k) = \frac{m + \lambda M}{M} \quad \Delta_i(k) + \lambda M, \quad \lambda \in (0, 1)
$$

Generally taken as 0.5

The correlation degree was calculated, that is, the gray correlation degree between the comparison sequence and the reference sequence was found, as shown in Eq. (9):

$$
\gamma_i(k) = \frac{1}{n} \sum_{i=1}^{n} \gamma_i(k), \quad i = 1, 2, 3...n
$$

The analysis results show that during the operation of the office building fresh air system, the gray correlation between the subjective satisfaction of the indoor personnel and the indoor environmental parameters during the operation of the indoor air system is as follows: Temperature > Fresh air volume > CO2 concentration > Relative humidity > Air velocity > PM2.5 concentration. That is, the proportion of the influence of indoor environmental parameters on the subjective satisfaction of indoor personnel is Temperature, Fresh air volume, CO2 concentration, Relative humidity, Air velocity, and PM2.5.

4. Discussion

4.1. Objective and subjective comparative analysis

The subjective and objective data comprehensively reflect the impact...
of the summer fresh air system on the indoor environment of office buildings. The analysis of objectively measured data shows that the changes in indoor environmental parameters meet the design requirements; however, the subjective questionnaire results indicate that the indoor personnel satisfaction is low, and the subjective satisfaction of the indoor personnel has not been improved on the premise of good indoor environmental parameters. There are two main reasons for the problems found in this study. First, the operation and maintenance management of building air conditioning systems have an important impact on changes in indoor environmental parameters. According to an investigation by the operation and maintenance department, there are problems derived from actions such as closing the fresh air system or shortening the operating time of the fresh air system to reduce the energy consumption of the fresh air system in summer. Second, through actual testing of the indoor environmental parameters, it was found that although some data met the relevant design standards, a large quantity of data were still outside the recommended values. Not only does this type of values affect the subjective feelings of indoor personnel, but also the differences in working conditions, physical health, and other factors affecting these feelings. Relevant design standards propose design values for environmental parameters based on the needs of an average person. ASHRAE stipulates that the thermal comfort of indoor personnel must reach 80%. Within a reasonable range, there are still some differences in the subjective satisfaction of the personnel.

4.2. Analysis of factors affecting staff satisfaction

Comparing and analyzing the Spearman’s correlation analysis results and gray correlation analysis results of the subjective satisfaction of the indoor environment personnel, it can be observed that the main factors affecting the satisfaction of indoor personnel were the same, and the indoor air temperature affected this satisfaction.

Regarding Figs. 5 and 8, the measured indoor air temperature of the office building mainly varies within the range of 23–28 °C, and the measured indoor air relative humidity mainly varies within the range of 30%–60%. Thus, there is still a large amount of data distributed in the not recommended values. From the analysis of the results of the questionnaire, it can be found that the average satisfaction of the indoor staff on the indoor air temperature was 3.61/5 and the average indoor relative humidity satisfaction was 3.51/5, which were far lower than the very satisfactory value of 5. According to the analysis of the differences between subjective and objective data, it can be observed that the indoor thermal environment is mainly adjusted by the air conditioning system, and the air conditioning system is closely related to the actions of the operation and maintenance management department and indoor personnel adjustment of this system. The recommended design value of the indoor environment parameters given by the relevant design standards for air conditioning systems is the average comfort value range, which is the basis of the air conditioning system design and cannot be used as a basis for judging the comfort needs of all indoor personnel.

People’s perception of CO₂ is more sensitive than that of PM₂.5, and hence CO₂ is often used as an index to evaluate indoor air quality, even though the harm caused by PM₂.5 to the human body is not denied. Long-term tests have been carried out to analyze changes in indoor air quality in this office building. As shown in Figs. 9 and 10, most measured values of CO₂ concentration at each measurement point of the office building, except for some data higher than the 1000 ppm specified in the standard, were distributed between 400 and 1000 ppm. It can be found from Figs. 11 and 12 that the median measured value of indoor PM₂.5 concentration is mainly distributed between 10 and 75 μg/m³, and there is a phenomenon of data exceeding the standard at individual measurement points. The subjective questionnaire survey results showed that the average indoor staff satisfaction with indoor air quality was 3.66/5.

As shown in Fig. 15, the measured fresh air volume during the operation of the fresh air system satisfied the design requirements. The indoor CO₂ concentration in the office building was tested for 8 h of fresh air system operation during a normal working day and 4 h during part of the working day. The required fresh air volume values at different concentrations were calculated using the steady-state difference method. It was found that when the indoor CO₂ concentration was maintained at 600–800 ppm, the required fresh air volume per capita was higher than the standard value, and when the concentration was maintained at 1000 ppm, the required fresh air volume per capita fluctuated around the standard value of 30 m³/h. Therefore, under the condition of relatively stable indoor personnel and workload in the office building, the size of the fresh air volume can be appropriately adjusted according to the changes in indoor CO₂ concentration to achieve the purpose of energy saving under the premise of fully ensuring indoor air quality. This study found that there are numerous printers and other photocopying equipment in the office building that are frequently used. Because of ink volatilization and other factors, this leads to relatively poor air quality in some locations. Further, the lack of a reasonable design of the location of air outlets in some rooms results in poor local airflow organization, as fresh air cannot be sent to the work and breathing areas where office workers are located.

As can be observed in Fig. 13, the indoor air velocity of the three normal working days during the test period is less than or equal to 0.3 m/s, thus meeting the design requirements of the indoor air velocity of air-conditioned office buildings in summer. The results of the subjective questionnaire analysis showed that the average satisfaction value of office workers with indoor air velocity was 3.32/5. In response to the problem of low satisfaction of indoor personnel with the airflow velocity, this study found feedback of some personnel about the existence of an indoor blowing sensation, which caused discomfort. In addition, the satisfaction level of the airflow velocity of office workers in air-conditioned rooms is largely inseparable from the noise generated by the air velocity at the air outlet. In office buildings with air conditioning or fresh air outlets, varying degrees of noise exist, and in newly renovated offices there is relatively less air noise. Varying degrees of air conditioning or fresh air outlet velocity determine the degree of noise reverberation; that is, with a high velocity, the general air outlet noise is relatively large, and vice versa. Some indoor personnel choose to reduce the velocity to reduce the generation of noise. However, a low velocity leads to poor indoor air circulation, which affects the local thermal comfort and air quality, which in turn affects the indoor personnel’s satisfaction with the environment.

4.3. Operation mode of office building fresh air system with normalized epidemic: discussion and suggestions

Based on the above analysis, it is known that before the outbreak of the COVID-19 epidemic, the fresh air conditioning system of the office building could ensure the quality of the indoor environment by running it 4 h per day. With the outbreak of COVID-19, it is now generally believed that maintaining the operation of the air conditioning system and increasing the amount of ventilation in buildings can effectively reduce the probability of personnel being infected (Agarwal et al., 2021; Junzhou, Ziwei & Xudong, 2020).

The air conditioning system of this office building consists of a fan coil and a fresh air system. According to the technical requirements of the emergency measures guide for the operation and management of office buildings in response to COVID-19, the following measures can be taken during the operation of the air conditioning system to meet the needs of use during the outbreak (Architectural Society of China, 2020; Li, Yanggang & Peng, 2020): (1) to extend the operation time of the fresh air system, to open the ventilation system in advance before work starts on weekdays, and to delay the closure of the ventilation system after work; (2) to increase the volume of fresh air and number of air changes, even taking actions such as opening the external windows to improve the room ventilation and air exchange; (3) to strengthen the operation and maintenance management of the air conditioning system,
“strengthen the cleaning, timely inspection,” to ensure the cleanliness of the source of fresh air volume; (4) to improve the filtration level of the fresh air system and seal the edge of the filter to prevent air bypass at the edge of the filter; and (5) to add some air purification devices that can effectively reduce the concentration of indoor pollutants.

Through an actual test of the indoor environment of the office building and the survey of personnel satisfaction, the results show that the indoor heat and humidity levels and indoor air quality of this building under the existing operation mode meet the provisions of the standard. Owing to the lack of comprehensive and timely maintenance management actions and individual differences in the indoor personnel, the subjective satisfaction of this personnel varies greatly, which also shows that the indoor environment of the office building still has room for improvement. The probability of infection under two different fresh air system operation strategies was calculated. It is clear that the probability of infection in the two operation strategies is less than 5%; however, the strong pathogenicity of the virus causing COVID-19 cannot be neglected. To meet the requirements during the COVID-19 epidemic period and after normalization of the epidemic, the operation and management of the air conditioning system should be improved to ensure the quality of the indoor environment. The time spent by office workers indoors is long (8 h or even longer). Thus, personal protection should be strengthened at all times with measures such as wearing masks, maintaining a safe distance between occupants, and detecting the body temperature of people entering the room. Those with abnormal body temperature and those who do not feel well should not enter the office area.

5. Conclusion

In this study, the indoor environmental parameters of an office building in Beijing during the summer were tested, and the satisfaction of indoor personnel was investigated from both objective and subjective aspects.

1. Through the actual testing of indoor environmental parameters such as air temperature, relative humidity, CO₂ concentration, PM₁₀ concentration, Air velocity, and Fresh air volume, it was found that the environmental parameters are maintained within the range of the air conditioning interior design parameters required by the Design Code for Heating, Ventilation, and Air Conditioning in Civil Buildings. However, a large number of data still deviate from the recommended values of the design standards. At the same time, the analysis of the subjective survey of indoor personnel satisfaction showed that the average value of indoor personnel satisfaction with each environmental parameter was generally low.

2. The study compiled the questionnaires of indoor personnel’s subjective feelings about the indoor environment, analyzed the Spearman correlation between indoor environmental parameters and personnel’s subjective satisfaction, and conducted a gray correlation analysis by combining the actual measured data of indoor environmental parameters with personnel’s satisfaction with the indoor environment. The results of the Spearman correlation and gray correlation analyses were consistent, and it was determined that indoor air temperature and indoor air quality were the most important factors affecting the satisfaction of indoor personnel.

3. The probability of infection of indoor personnel under two modes of operation of the fresh air system was calculated, and the probability of infection under both modes is less than 5%. However, because the virus causing COVID-19 is extremely infectious and pathogenic, it is necessary to ensure the health of personnel and normal working conditions until normalization of the epidemic.

4. To cope with COVID-19 and the regular prevention and control of epidemics, the fresh air system in office buildings should increase the source of fresh air volume; (4) to improve the filtration level of the fresh air system and seal the edge of the filter to prevent air bypass at the edge of the filter; and (5) to add some air purification devices that can effectively reduce the concentration of indoor pollutants.

5. This study investigated the impact of fresh air systems on the indoor environment and personnel satisfaction in office buildings during the summer in Beijing. The results of this analysis can support the improvement of the indoor environment of office buildings, enhance the comfort and satisfaction of personnel, and reduce the energy consumption of buildings. Simultaneously, in the context of the COVID-19 pandemic, this study provides a reference for ensuring the health of indoor personnel and improving the operation and management of fresh air systems in office buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Agarwal, N., Meena, C. S., Raj, B. P., Saini, L., Kumar, A., Gopalakrishnan, N., et al. (2021). Indoor air quality improvement in COVID-19 pandemic: Review. Sustainable Cities and Society, 79, Article 102942.

Agha-Hosein, M. M., El-Jouzi, S., Elshalmi, A. A., Ellis, J., & Williams, M. (2013). Post-occupancy studies of an office environment: Energy performance and occupants’ satisfaction. Building and Environment, 69, 121–130.

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Catzfgyiotou, M., & Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: A review of the literature. Building and Environment, 105, 369–389.

Andargie, M. S., & Azar, E. (2019). An applied framework to evaluate the impact of indoor office environmental factors on occupants’ comfort and working conditions. Sustainable Cities and Society, 46, Article 101447.

ANSI/ASHRAE 55-2010. (2010). Thermal environmental conditions for human occupancy, the ashe standards committee (p. 2010). The American National Standrds Institute.

Architectural Society of China. Guidelines for Emergency Operation and Management of Office Buildings for Dealing with ‘Novel Coronavirus’. T/ASC 08-2020 [S].

Arai, I., Mahyuddin, N., & Shafiq, P. (2017). A review on Indoor Environmental Quality (IEQ) and energy consumption in buildings based on occupant behaviour. Facilities, 66, 684-695.

ASHRAE. (2017). ASHRAE standard 55-2017 thermal environmental conditions for human occupancy. Ashrae.

Cao, B., Ouyang, Q., Zhu, Y., Huang, L., Hu, H., & Deng, G. (2012). Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. Building and Environment, 47, 394–399.

Chan, J. F., Yuan, S., & & k. H. (2020). A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission:A study of a family cluster[J]. Lancet (London, England), 395(10223), 514-523.

China Indoor Environment Test Center. Technical specification of the test methods for the air cleaner to remove particulate matter PM2.5 (GSH/J2011-1), Beijing, China, (2011). (In Chinese).

Choi, J. H., Lofthens, V., & Aziz, A. (2012). Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines (pp. 167-175). Elsevier Ltd, Dayur, DengD., & Jinyan, Cai C. (2007). Carbon Dioxide Pollution and Air change flow inside classroom. Environmental Science & Technology, (99), 45-47 +117-118.

Deng, J. L. (1992). Grey control systems (2nd ed.). Wuhan: Huazhong University of Science and Technology Press.
