Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company’s public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Study on indoor air quality and fresh air energy consumption under different ventilation modes in 24-hour occupied bedrooms in Nanjing, using Modelica-based simulation

Fusuo Xu, Zhi Gao

School of Architecture and Urban Planning, Nanjing University, 22 Hankou Road, Nanjing, Jiangsu Province 210093, China

ARTICLE INFO

Article history:
Received 13 November 2021
Revised 13 December 2021
Accepted 19 December 2021
Available online 23 December 2021

Keywords:
Modelica
Indoor pollutant
Fresh air energy consumption
Ventilation mode

ABSTRACT

COVID-19 has forced people to spend more time working and studying at home; in particular, people who share an apartment stay in their respective bedrooms almost all day. This study investigated the impact of ventilation modes on the indoor air quality (IAQ) of 24-hour occupied bedrooms and provided ventilation suggestions for people who stay in their bedrooms for a long time during the pandemic compared with the study of traditional apartment ventilation. In addition, the fresh air energy consumption of different ventilation modes was compared to help residents save energy. In summer, a window-opening ratio of 25% (0.3 m²) could effectively improve IAQ. However, it is not recommended to use natural ventilation in winter because the outdoor PM2.5 concentration is too high. Moreover, the fresh air energy consumption for the automatic control window-opening ratio was 1/5 of that for a window-opening ratio of 25%. In the whole summer, it can save 196.1 kWh compared to a fixed window-opening ratio of 25%. Fresh air systems could greatly improve IAQ and lower energy consumption regardless of the season. However, the automatic-control window-opening ratio mode has lower energy consumption, which is approximately 0.37 times that of fresh air systems in summer.

© 2021 Elsevier B.V. All rights reserved.

1. Introduction

Indoor air pollution has become a looming threat to human health because currently, people are spending most of their time indoors in buildings [1–3]. In particular, the COVID-19 outbreak has forced people to stay indoors for study, work, and other activities leading to greatly reduced outdoor time. Air pollutants enter rooms in two ways: 1) through indoor emissions, such as formaldehyde, ozone, and VOCs emitted by furniture, home appliances, and PM2.5, emitted by cooking activities and indoor smoking [4,5]; and 2) through outdoor pollutants transported indoors through doors and windows [6,7]. Therefore, it is vital for people's health and sustainable development to explore both the impact of indoor and outdoor pollutants on indoor air quality (IAQ) and how to obtain good indoor air quality with low energy consumption.

To improve indoor air quality, different standards put forward different requirements for indoor fresh air supply [8,9]. Natural ventilation and mechanical ventilation are two ways to provide fresh air indoors. Since natural ventilation does not require the installation of fresh air equipment, it only needs to introduce outdoor air through the exterior windows of the building, so natural ventilation has become the most commonly adopted method of fresh air supply. The way that mechanical ventilation provides indoor fresh air requires the installation of a mechanical air supply system, which can also be handled by fresh air equipment such as fresh air units and total heat exchangers before being sent indoors. Fresh air processed by fresh air equipment can obtain better air quality than natural ventilation [10].

The influence of natural ventilation on indoor air quality has attracted extensive attention from researchers [11,12]. Good natural ventilation can improve indoor air quality and comfort with low or no energy consumption [13]. Tian et al. [14] found that due to the significant difference in the frequency and time of window opening in different seasons, the usual random opening of windows caused a 40.3% change in particulate matter ≤ 0.1 μm (PM0.1) concentration. Xiao et al. [15] studied the effect of the window opening on indoor particle concentrations in the cold region of China through indoor experiments. When the window was opened, decay rates up to 19.09 h⁻¹ for 2.5–10 μm particles and up to 9.73 h⁻¹ for particulate matter ≤ 2.5 μm (PM2.5) were observed. Other researchers have studied the influence of window opening on air quality and indoor temperature in different types of buildings, such as schools [16], hospitals [17], and commercial offices.
While natural ventilation affects IAQ, it also significantly affects the energy consumption of fresh air and the overall building energy consumption [19]. Moreover, the effects of natural ventilation on indoor acoustic [20], temperature, smoke during fires [21], and the infectious risk of COVID-19 [22] were also investigated.

For building ventilation and pollutant transportation simulation, multizone models have an advantage in that the simulation takes less time than computational fluid dynamics (CFD) simulations. Many multizone models (such as CONTAM, COMIS, and Modelica models established by the multizone method [23]) have been widely used to study pollutant transportation [24–27]. The multizone model can also be coupled with other platforms to obtain a more accurate flow field and parameter values in a specific space. Heibati et al. [28] developed a comprehensive model (CONTAM and WUFI coupled) to predict the performance of indoor air quality, humidity, and thermal comfort. The results show that the airflow data corrected by the CONTAM-WUFI collaborative simulation mechanism have better accuracy when replacing the airflow input data assumed by the user. Tian et al. [29] implemented coupled models of the fast fluid dynamics model and the Modelica model to determine the optimal location of the thermostat to achieve the best thermal comfort, the least energy consumption, or both. Although the coupling simulation of the multizone model with CFD software or other software will obtain a more accurate flow field and accuracy in a certain region, it will spend more simulation time when there are many simulation cases. In recent years, the Buildings Library developed by Wetter et al. [30] has provided great convenience for the simulation of other researchers in the field of building environments on the Modelica platform. Fu et al. [31] used the Modelica Buildings Library to study the energy consumption of a data center. Simulation results showed potential energy savings of up to 24% by resolving identified control-related issues and optimizing the supply air temperature. The Modelica simulation platform has been widely employed to study ventilation, heat transfer, and energy systems because of the advantage of easily established new models and control modules [32–35].

The outbreak of COVID-19 and its rapid spread worldwide have prompted many governments to implement stay-at-home orders to limit its spread. Therefore, people spend more time working and studying at home. This phenomenon has led young people who share apartments to stay in their bedrooms almost during the whole day. Therefore, in the context, the IAQ of bedrooms is of the highest importance for the health of residents. The energy consumption of bedrooms is also essential for living expenses within a limited economic capacity. Therefore, the type of ventilation mode that can achieve good IAQ and low energy consumption in a bedroom is a worthwhile issue to study. This study made the following assumptions:

1) People who share an apartment always stay in their bedrooms during the whole day. For example, during the COVID-19 pandemic and the subsequent stay-at-home orders, people studied and worked in their bedrooms.

2) The building energy consumption caused by the building envelope load always exists regardless of whether fresh air is introduced indoors (natural ventilation or fresh air system). Therefore, this study only evaluates fresh air energy consumption.

Overall, this study used Modelica-based simulation to investigate the relationship between IAQ and fresh air energy consumption for different bedroom ventilation methods and provides suggestions for building residents on the choice of the fresh air system. The rest of the paper is organized as follows. Section 2 introduces the model parameters (building parameters and indoor and outdoor environmental parameters), energy consumption calculation methods, and model validation. Section 3 discusses the variation in indoor pollutant concentrations for different ventilation modes, the fluctuation range of indoor temperature under limited cooling and heating capacity of air conditioners, and fresh air energy consumption. Finally, Section 4 presents the conclusions of the study and provides optimal ventilation suggestions for good IAQ and low energy consumption.

2. Methodology

To simulate the indoor air quality and fresh air energy consumption of different fresh air supply modes in 24-hour occupied bedrooms, it is necessary to determine the model parameters and establish the Modelica model. The main research flow is shown in Fig. 1. In subsection 2.1, the outdoor meteorological parameters in Nanjing were statistically analyzed. In addition, a typical apartment space layout was adopted, and the air conditioning performance parameters and energy consumption calculation method are presented in subsection 2.2. In subsection 2.3, the Modelica models of different fresh air supply modes created according to the above parameters were introduced. The IAQ standards used in this study are shown in subsection 2.4. Finally, the validation of the Modelica model was conducted in subsection 2.5.

2.1. Outdoor meteorological parameters

Nanjing is located in the hot-summer and cold-winter climate zones of China. Fig. 2 shows the temperature and wind velocity variation curves of the outdoor meteorological parameters in Nanjing. The hottest months in Nanjing are July and August, and the coldest months are December and January. In this study, the weather parameters of the slight heat day in July and the lesser cold day (Chinese solar terms) in January represent the outdoor weather parameters in summer and winter, respectively.

Four outdoor meteorological monitoring stations—Pukou, Xuanwu Lake, Xianlin, and Zhonghuamen—were selected to analyze the outdoor pollutants in the different azimuths of Nanjing. The variations in the outdoor pollutant concentrations at each site in January and July are shown in Fig. 3. The PM2.5 and ozone concentrations at each time point at these four meteorological monitoring stations were similar, and the variation trend was the same in a month. Therefore, the pollutant concentrations at these four stations could well represent the outdoor pollutant concentrations in Nanjing city. The average pollutant concentrations at the four stations were used as the outdoor pollutant concentration parameters, as shown in Fig. 4. In July, the average outdoor PM2.5 and ozone concentrations were 22.2 \( \mu g/\text{m}^3 \) and 71.8 \( \mu g/\text{m}^3 \), respectively; in January, these values were 80.4 \( \mu g/\text{m}^3 \) and 38.5 \( \mu g/\text{m}^3 \), respectively. This study selected the average concentration of outdoor pollutants in July and January to represent the outdoor pollutants in summer and winter, respectively. In Nanjing, the main outdoor pollutants are ozone in summer and PM2.5 in winter.

2.2. Indoor environmental parameters

A representative three-bedroom apartment was used in this study. It was assumed that the three-bedroom apartment is on shared rent by four people: two people occupying the large bedroom (Bedroom A) and one person in each of the two small bedrooms (Bedroom B and Bedroom C), as shown in Fig. 5; this assumption was made because this mode of sharing an apartment is a common phenomenon for young people in China. People spend
almost 24 h a day in their bedroom, such as during the pandemic and the implementation of the stay-at-home order. Moreover, the maximum openable area of the window in Bedroom A is 1.2 m². Air-conditioned rooms are the bedrooms and the living room. A separated-type air conditioner for Bedroom A was used to adjust the indoor temperature. The performance parameters of the air conditioners are listed in Table 1. According to the design standard, the indoor temperature was set at 25 °C in summer and 20 °C in winter [8].

Two fresh air supply schemes were employed in this study. Plan A provided fresh air to Bedroom A via natural ventilation (fresh outdoor air entered through the bedroom window). Plan B used a fresh air system (total heat exchanger) to provide fresh air to Bedroom A and to the other rooms. The required volumetric flow rate of fresh air to each room was set according to standard [8], as shown in the line chart in Fig. 5. After outdoor air entered the air supply pipeline, it passed through the primary effect filter, activated carbon filter, and PM2.5 filter in the total heat exchanger and then flowed to the room. The purification efficiency of the total heat exchanger was assumed to be 80%.

The power of the total heat exchanger was 300 W, and the electrical energy consumption was shared in proportion to the fresh air volume of each room. That is, the energy consumption of the total heat exchanger of Bedroom A was 46.2 W. The total heat exchanger in this study set a heat transfer efficiency of 60% in summer and 68% in winter according to the actual equipment configuration. Therefore, the temperature of the fresh air sent into the room can be calculated as follows:

\[
t_s = t_0 - \eta_t(t_0 - t_e)
\]

where \(t_s\) (°C) is the supply air temperature, that is, the temperature of the fresh air sent into the room, \(\eta_t\) is the temperature efficiency of the total heat exchanger, and \(t_0\) (°C) and \(t_e\) (°C) are the outdoor air and exhaust indoor air temperatures, respectively.

When the natural ventilation method is used to provide fresh air, the air conditioner is responsible for all the energy consumption of fresh air. When the total heat exchanger is used to provide fresh air, both the total heat exchanger and air conditioner are responsible for the fresh air energy consumption.

The building load (except for the fresh air load) \(Q_B\) including heat transfer of building envelope, heat dissipation of human body and electrical equipment is shown in the histogram in Fig. 5. This study conservatively evaluates the ability of air conditioning to handle fresh air temperature in consideration of the largest \(Q_B\) under typical weather conditions. The maximum building cooling load of Bedroom A in summer was 1079 W, and the maximum building heat load in winter was 398 W. The separated-type air conditioner in Bedroom A was responsible for the building load and fresh air load (all in Plan A, part in Plan B). The cooling and heating capacity of the air conditioner used was responsible for the energy consumption of fresh air and was calculated as follows:

\[
C_{FM} = C_R - C_B = C_R - \frac{Q_a}{a}
\]

where \(C_{FM}\) (W) is the maximum cooling or heating capacity of the air conditioner for fresh air. Owing to defrosting, dust deposition, and other reasons, the actual cooling or heating capacity of the air conditioner was less than the rated cooling and heating capacity \(C_R\) (W). Therefore, in this study, a correction factor of \(a\) (\(a = 0.7\)) was used. \(C_B\) is the cooling or heating capacity of the air conditioner for the building load. Therefore, the maximum cooling capacity of the air conditioner for fresh air is 3058.6 W, and the maximum heating capacity is 5231.4 W. The maximum fresh air loads that the air conditioner could handle were 2141 W and 3662 W, respectively.

Fig. 6 shows the fitting curve of the relationship between the cooling and heating capacities and the energy consumption of the air conditioner. The fresh air energy consumption can be calculated using Eq. (3).

\[
P_F = \frac{C_F}{C_F + C_B} \times P_T
\]
where $P_F$ (W) is the energy consumption of the air conditioner for fresh air, $P_T$ is the total energy consumption, including the fresh air load and building load, and $C_F$ is the actual cooling/heating capacity of the air conditioner for fresh air.

Based on Chen et al. [36], this study used a PM$_{2.5}$ emission intensity of 120 $\mu$g/s for noon and evening cooking activities and a PM$_{2.5}$ emission intensity of 60 $\mu$g/s for morning activities. It was assumed that 2% of the pollutants can be transmitted from the kitchen to a bedroom when the bedroom door is closed [37].

The intensity and frequency of the PM$_{2.5}$ pollution sources for Bedroom A are shown in Fig. 7. Zhang and Jenkins [38] studied the ozone emission intensity of 17 small household appliances, including fruit and vegetable washers and facial steamer.

However, these small household appliances are used less frequently and...
are not typically used in bedrooms; therefore, it was assumed that there was no ozone source in bedrooms. In addition, it was assumed that the initial background concentration of indoor pollutants was 30% of the outdoor concentration [39].

In addition to indoor pollution sources that significantly impact indoor pollutant concentration levels, the deposition of pollutants also affects the indoor pollutant concentration level. The pollutant deposition module used in this study was built using Eq. (4) [40].

---

Table 1
Performance parameters of the air conditioner.

| Type    | Capacity (W) | Power (W) | Air Flow Volume (m³/h) |
|---------|--------------|-----------|------------------------|
| Cooling | 3500 (300 ~ 4600) | 885 (90 ~ 1580) | 700 |
| Heating | 4800 (300 ~ 5800) | 1245 (90 ~ 1685) | |

---

Fig. 5. Diagram of the research target and the different air supply schemes.

Fig. 6. Performance curve of the air conditioner.
\[ R_x = \nu_d \times A_t \times \rho_{\text{air}} \times C_a \]  

where \( \nu_d \) (m/s) is the deposition velocity of the pollutants and \( A_t \) (m\(^2\)) is the deposition surface area. Ignoring the influence of different indoor decoration materials and ventilation rates, the deposition velocity of PM\(_{2.5}\) and ozone in this study was set at 0.04 cm/s \([41,42]\). The deposition surface area of Bedroom A is 108 m\(^2\), \( \rho_{\text{air}} \) (kgair/m\(^3\)) is the density of air, and \( C_a \) (kg/kgair) is the mass fraction of pollutant \( a \). Therefore, the concentration of pollutant \( a \) is the product of \( \rho_{\text{air}} \) and \( C_a \).

2.3. Modelica model

The Modelica model was created using the parameters of the previous section based on OpenMoldelica v1.16.5, as shown in Fig. 8. Three models (Models 1–3) composed of different modules (Modules A–F) were used to study the effects of three fresh air supply methods (fixed window-opening ratio, automatic-control window-opening ratio, and using fresh air equipment) on IAQ and fresh air energy consumption. Module A is the air conditioner model, which adjusts the indoor environment temperature through a proportion integration differentiation (PID) controller within the cooling and heating capacity of the air conditioner. Module B is the window-opening model, which can adjust the window-opening ratio on a scale of 0–1. Modules C and D are the pollutant deposition and pollutant emission models, respectively. Outdoor temperature, wind velocity, window orientation, and other factors affect indoor natural ventilation. Module E was used to read the outdoor meteorological parameters and set the window orientation. For the fixed window-opening ratio in this study, Module F was used to define five different window-opening ratios (f1 connected to a2), which were 0%, 25%, 50%, 75%, and 100%. Moreover, an automatic control module was defined to adjust the window-opening ratio according to the indoor pollutant concentration (g1 connected to a1 and g2 connected to a2). The relationship between the pollutant concentration and the window-opening ratio is shown in Fig. 9. The standard ACM1 is the normal monitoring standard, and the standard ACM2 is the strict monitoring standard. When the outdoor pollutant concentration is very high, for example, in winter, natural ventilation leads outdoor pollutants into the room, and the indoor air quality cannot be improved. Therefore, many buildings with high IAQ requirements usually use air purification equipment or fresh air systems. In this study, a total heat exchanger Module H was defined in Modelica to provide fresh air for indoors.

2.4. IAQ standard

Comprehensively considering the air quality standards of the United States and China \([43,44]\), in this study, when the indoor ozone concentration is lower than 70 \( \mu \)g/m\(^3\), IAQ is good. In the bedroom, the ozone concentration is usually very low, so a moderate category is not set in this study to evaluate the IAQ affected by ozone. The impact of PM\(_{2.5}\) on health has recently attracted much attention in China. Hence, this study set good and moderate categories for quantitative analysis of PM\(_{2.5}\): IAQ is moderate when its concentration is lower than 70 \( \mu \)g/m\(^3\) and good when its concentration is lower than 35 \( \mu \)g/m\(^3\) (Fig. 10).

2.5. Validation

The validation was conducted based on OpenModelica v1.15.0 and CONTAMW 3.2.0.2 (W stands for CONTAM version in Windows platform) because the accuracy of CONTAM simulation has been widely recognized \([45]\). As shown in Fig. 11, there are three rooms in the validation model: the large room is located on the second floor, and the two small rooms are located on the first floor. There is a 2.2 m\(^2\) door between the two small rooms so that the two rooms have air exchange. In addition, the rooms between the first and second floors have air exchange through the orifices between them. Table 2 shows the ventilation and penetration parameters of doors and orifices setting according to the literature \([20]\). As shown in Fig. 11(d), the difference in ventilation rate between the CONTAM and Modelica models was less than 1% at the maximum mass flow rate (i.e., ventilation flow rate of the door). The mass flow also has a good consistency for other orifices. In addition, the Modelica simulation results of the present work are in good agreement with the results of Wetter et al. \([20]\). Overall, the simulation results of Modelica are reliable.
3. Results and discussions

This section discusses and analyzes the simulation results of air quality and energy consumption affected by different fresh air supply modes. Since there is no need to turn on air conditioning in spring and autumn in Nanjing and outdoor pollutant concentrations such as PM2.5 are low, there will be no caused fresh air energy consumption. Therefore, this study only discussed the situation of using air conditioning in summer and winter. In subsection 3.1, the effects of natural ventilation with a fixed window-opening on indoor air quality and indoor ambient temperature in summer and winter are discussed. According to the conclusion in subsection 3.1.1, natural ventilation is not suitable for use in winter in Nanjing, so the natural ventilation of automatic-control window-opening ratio was only discussed in summer in subsection 3.1.2. When fresh air equipment was used to provide fresh air for the bedroom, the variation in IAQ and indoor temperature in one day were analyzed in subsection 3.2. In subsection 3.3, the fresh air energy consumption caused by different fresh air supply modes was analyzed and compared. Moreover, the optimal ventilation strategy was given by comprehensively considering IAQ and fresh air energy consumption.

3.1. Natural ventilation

3.1.1. Fixed window-opening ratio

In this section, Bedroom A is referred to as “bedroom.” Fig. 12 shows the variation in pollutant concentrations under different fixed window-opening ratio conditions in summer. There was no ozone source in the bedroom, and outdoor ozone entered the bed-
room through the window gap when the window was closed. The ozone deposition rate was greater than the rate of ozone entering the room from the outside, decreasing the indoor ozone concentration and gradually reaching the equilibrium state. After 24 h, the indoor ozone concentration was approximately $3 \text{ mg/m}^3$, which is far below the limit value of the air quality standard. In summer, the outdoor PM$_{2.5}$ concentration level in Nanjing was low; hence, natural ventilation can dilute high PM$_{2.5}$ concentrations indoors. However, when the window-opening ratio was 0%, the outdoor air entering the room through the window gap was insufficient to dilute the indoor polluted air to a concentration below the air quality standard. The indoor PM$_{2.5}$ concentration exceeding $35 \text{ mg/m}^3$ was 13.06 h, the time exceeding $70 \text{ mg/m}^3$ was 4.70 h, and the peak value of the PM$_{2.5}$ concentration was 114.96 mg/m$^3$, which is harmful to the health of people. As shown in Fig. 12(b), when the window-opening ratio was 25%, natural ventilation could effectively reduce indoor PM$_{2.5}$. The time taken for the PM$_{2.5}$ concentration to exceed $35 \text{ mg/m}^3$ was reduced to 2.59 h, which does not exceed 70 mg/m$^3$. The indoor PM$_{2.5}$ concentration exceeded 35 mg/m$^3$ was only 0.48 h when the window-opening ratio increased to 50%, as shown in Fig. 12(c). When the window-opening ratio was 75% and 100%, as shown in Fig. 12(d) and (e), the indoor PM$_{2.5}$ concentration could no longer exceed 35 mg/m$^3$, but the cooling capacity of the bedroom air conditioner was not sufficient to achieve an indoor temperature of approximately 25 °C, as shown in Fig. 13. With an increase in the window-opening ratio, the bedroom air change per hour (ACH) increased, as shown in Fig. 14. However, an increase in the window-opening ratio increased the energy consumption of the air conditioner. In summer, natural ventilation with 25%, 50%, 75%, and 100% window-opening ratios introduced air with high ozone concentrations into the bedroom. However, the highest indoor ozone concentration was still in the good IAQ category.

In summer, opening windows can effectively improve indoor air quality, but a large window-opening ratio significantly increases building energy consumption. In addition, the indoor temperature cannot be maintained at the setting value, leading to a decline in indoor comfort. When the window-opening ratio was greater than 25%, the 24-hour average concentration of PM$_{2.5}$, in the bedroom, did not exceed 35 mg/m$^3$, and the maximum concentration did not exceed 70 mg/m$^3$, as shown in Fig. 14. In addition, the maximum and average ozone concentrations in the summer were in the good category. This study recommends a window-opening ratio of 25% in the bedroom during cooking in summer, approximately 0.3 m$^2$, and closing the bedroom window when not cooking to avoid wasting air conditioning power.

Fig. 15 and Fig. 16 show the variation in pollutant concentration and indoor temperature under a fixed window-opening ratio in winter. PM$_{2.5}$ is the main outdoor pollutant in winter, and the outdoor ozone concentration is markedly lower than 35 mg/m$^3$. As shown in Fig. 17, the maximum and average ozone concentrations were low. The PM$_{2.5}$ concentration rises rapidly during cooking if

---

**Table 2**
The parameters for ventilation and infiltration [20].

| Parameter name                      | Orifice | Door |
|-------------------------------------|---------|------|
| Opening flow coefficient /$C_D$     | 0.65    | 0.78 |
| Flow exponent /$n$                  | 0.50    | 0.78 |
| Opening area /$A$ (m$^2$)           | 0.01    | 2.2  |
| Width /$w$ (m)                      | /       | 1    |
| Height /$h$ (m)                     | /       | 2.2  |
| Number of interfaces /$n_{com}$     | /       | 10   |
| Minimum velocity /$v_e$ (m/s)       | /       | 0.001|

---

F. Xu and Z. Gao Energy & Buildings 257 (2022) 111805
the windows are closed, as shown in Fig. 17(a). After cooking, the PM$_{2.5}$ concentration decreases due to pollutant deposition and infiltration ventilation. The PM$_{2.5}$ concentration in the bedroom exceeded 35 µg/m$^3$ and 70 µg/m$^3$ was 15.26 h and 5.38 h respectively, which can be harmful. When the windows were opened, indoor PM$_{2.5}$ concentrations quickly increased, as shown in Fig. 15(a), (b), (c), and (d). The maximum and average PM$_{2.5}$ concentrations exceeded the moderate category of the IAQ. In winter, owing to the large temperature difference between indoors and outdoors, when the window-opening ratio is 25%, the heating...
capacity of the air conditioner is not sufficient to ensure that the indoor temperature remains at the set value, as shown in Fig. 16. When the window-opening ratio was gradually increased to 50%, 75%, and 100%, the indoor temperature continued to decrease. The lowest indoor temperature was 2 °C when the window-opening ratio was 100%, which is not suitable for living. Regardless

Fig. 14. Statistics of average and maximum concentrations of pollutants and air change per hour under different window-opening ratios in summer.

Fig. 15. Variation in pollutant concentration under a fixed window-opening ratio in winter for (a) 0%, (b) 25%, (c) 50%, (d) 75% and (e) 100%.
of the window-opening ratios of 25%, 50%, 75%, and 100%, the indoor PM$_{2.5}$ concentration rose rapidly after opening the window, and it was always higher than the moderate category. Therefore, this study does not recommend the use of natural ventilation in winter.

3.1.2. Automatic-control window-opening ratio

The use of natural ventilation in winter is detrimental to indoor air quality. As shown in Section 3.1.1, natural ventilation in winter results in consistently higher indoor PM$_{2.5}$ concentrations than the moderate category. In addition, although ozone is the leading outdoor pollutant in summer, natural ventilation does not cause excessive indoor ozone concentrations or is harmful to human health. Therefore, we used PM$_{2.5}$ levels to study the IAQ under natural ventilation in summer in this section.

Fig. 18(a) shows the variation in the indoor pollutant concentration under the normal monitoring standard condition (ACM1). The natural ventilation of the automatic control maintained the indoor pollutant concentration at a low level while maintaining the indoor temperature around the set value (Fig. 19). The indoor PM$_{2.5}$ concentration did not exceed 70 µg/m$^3$ under the normal monitoring standard condition and exceed 35 µg/m$^3$ by approximately 2.06 h. Fig. 18(b) shows the variation in the indoor pollutant concentration under strict monitoring standard conditions. The indoor pollutant concentration showed a trend similar to that of the normal standard, and at 1.32%, its peak value was lower than that of the normal standard. The difference between ACM1 and ACM2 was not significant. Therefore, using a normal automatic control standard can ensure that the indoor pollutant concentration is within an acceptable range. The average concentrations of PM$_{2.5}$ and ozone for ACM1 and ACM2 did not exceed the acceptable level of air quality standards, as shown in Fig. 20. In addition, the maximum ozone concentration never exceeded the good category of IAQ. The average ACH of natural ventilation with an automatic-control window-opening ratio was smaller than that of the fixed window-opening reducing energy consumption. Overall, compared with the fixed window-opening ratio method, the automatic control method can better reduce the indoor pollutant concentration and maintain the indoor temperature environment at the set value.

3.2. Using fresh air equipment

Buildings with high IAQ requirements are usually employed in fresh air systems to supply fresh air. Fig. 21 shows the variation in the indoor pollutant concentration when the total heat exchanger provides fresh air to the apartment. As there is no ozone source in the bedroom, the ozone concentration is low in the room in both winter and summer seasons. In summer, when cooking activities begin, the rate of PM$_{2.5}$ transport to the bedroom is greater than the dilution rate of the indoor pollutant with fresh air; therefore, the indoor PM$_{2.5}$ concentration rises (Fig. 21(a)). When the cooking activity ends, the indoor PM$_{2.5}$ concentration decreases. However, breakfast cooking has a lower PM$_{2.5}$ emission rate than lunch and dinner cooking, and the PM$_{2.5}$ concentration in the bedroom does not exceed the moderate category.
During cooking activities conducted in the noon and evening, the time for the PM2.5 concentration to exceed 35 \( \text{mg/m}^3 \) was found to be 2.20 h, but it does not exceed 70 \( \text{mg/m}^3 \). As shown in Fig. 21(b), the outdoor PM2.5 concentration in winter is relatively high, and the PM2.5 concentration in fresh air filtered by the total heat exchanger will be slightly higher than that in summer. The dilution rate of polluted air in the bedroom by fresh air also decreased. Therefore, although the variation trend of indoor PM2.5 concentration in winter was the same as that in summer, the maximum value of PM2.5 concentration was higher in winter than in summer. During breakfast time, the PM2.5 concentration still did not exceed 35 \( \text{mg/m}^3 \). During lunch and dinner, the PM2.5 concentration exceeded 35 \( \text{mg/m}^3 \) was 2.50 h, but it did not exceed the moderate category of the IAQ standard. The air conditioner system can control the indoor temperature within the set temperature range in both the summer and winter seasons (Fig. 22). The 24-h average concentrations of ozone and PM2.5 are in the good category of IAQ standards (Fig. 23). In addition, the ACH of the bedroom that uses a total heat exchanger while meeting the fresh air demand of indoor personnel is less than that of a fixed window-opening ratio, thus saving fresh air energy consumption. Therefore, in both summer and winter, the fresh air system of the total heat exchanger can improve the indoor air quality very well.

### 3.3. Analysis of fresh air energy consumption

The fresh air energy consumption of the different fresh air supply methods is shown in Fig. 24. When the window was closed, the outdoor air could infiltrate indoors through the window gap. The energy consumption of fresh air in summer was minimal and could

---

**Fig. 18.** Variation in pollutant concentration under automatic-control window-opening ratio in summer for (a) ACM1 and (b) ACM2.

**Fig. 19.** Variation in indoor temperature values under the automatic-control window-opening ratio in summer.

**Fig. 20.** Statistics of average and maximum concentrations of pollutants and air change per hour under automatic-control window-opening ratios.
be ignored. The energy consumption of fresh air in winter was only 0.09 kW·h. When the fixed window-opening ratio was 25% in summer, the air conditioner could control the indoor temperature at 25 ± 0.5 °C, as shown in Fig. 25. The indoor PM$_{2.5}$ concentration and ozone concentration did not exceed 70 μg/m$^3$; the PM$_{2.5}$ concentration above 35 μg/m$^3$ was 2.59 h, as shown in Fig. 26. At this time, the IAQ of PM$_{2.5}$ was in the moderate category, the indoor ozone concentration was in the good category, and the energy consumption was only 2.56 kW·h. However, when the fixed window-opening was 25% in winter, the indoor PM$_{2.5}$ concentration exceeded the moderate category and markedly increased the building energy consumption. The energy consumption of fresh air was 33.49 kW·h; often, the indoor temperature could not be maintained within the set range. When the fixed window-opening ratio was more than 25% in winter, the air conditioning was always in the maximum power operation mode; the fresh air energy consumption was 34.02 kW·h. The indoor PM$_{2.5}$ concentration exceeded the moderate category, and the indoor environment temperature was extremely uncomfortable. Therefore, natural ventilation is not recommended in winter. In summer, when the fixed window-opening ratio increased from 25% to 50%, the time for PM$_{2.5}$ concentration to exceed the 35 μg/m$^3$ was shortened to one-fifth (0.48 h); however, the energy consumption also increased by 3.16 times. When the fixed window-opening ratio increased to 75% and 100%, the air conditioner’s cooling capacity was insufficient to maintain the indoor temperature within the fluctuation range with a setting value of ± 0.5 °C. Therefore, natural ventilation can be used in summer with a 25% window-opening ratio (0.3 m$^2$) in the bedroom without a fresh air system.

When the method of automatic-control window-opening ratio was used to provide fresh air in the bedroom, the time of the PM$_{2.5}$ concentration to exceed 35 μg/m$^3$ was further reduced compared with the use of natural ventilation with a 25% fixed window-opening ratio. Moreover, the indoor PM$_{2.5}$ concentration of natural ventilation of the automatic-control window-opening ratio did not exceed the moderate category. There were no significant differ-
ences in pollutant concentrations and energy consumption between strict and normal control standards. Therefore, it is sufficient to control IAQ by using the normal standard automatic control method. The fresh air energy consumption of the automatic-control window-opening ratio was one-fifth (only 0.48 kW-h) that of the 25% fixed window-opening ratio. Consequently, in summer, the automatic control window-opening ratio was better than the fixed window-opening ratio.

With rapid economic development and improved living standards, an increasing number of families in China have begun to install fresh air systems. When the fresh air system was used in the bedroom, the IAQ improved in both summer and winter (Fig. 26). In winter, the outdoor PM$_{2.5}$ concentration in Nanjing is high; this is one of the main sources of indoor PM$_{2.5}$. Therefore, natural ventilation can only aggravate indoor PM$_{2.5}$ in the winter. As a result, a fresh air system can effectively improve the indoor air quality. In winter, the total indoor fresh air energy consumption was 2.33 kW-h when the total heat exchanger was used. In summer, the time of the indoor PM$_{2.5}$ concentration exceeded 35 µg/m$^3$ when the fresh air system was used, similar to that when the automatic-control window-opening ratio was used. The total energy consumption of fresh air was 1.30 kW-h with the fresh air system, which was 2.7 times that with the automatic-control window-opening ratio. Therefore, this study recommends using a

![Fig. 24. Total fresh air energy consumption of different fresh air supply methods. THE stands for total heat exchanger.](image)

![Fig. 25. Percentage of indoor temperature within $T_{set} \pm 0.5$ °C (%) of different fresh air supply methods.](image)
fresh air system in winter and natural ventilation with an automatic-control window-opening ratio in summer to provide fresh air to the bedroom.

4. Conclusions

The COVID-19 pandemic and the subsequent stay-at-home orders confined people to their homes, largely restricting their outdoor activities, especially forcing those who share an apartment to spend almost 24 h in their bedrooms. Therefore, the IAQ of bedrooms is crucial for the health of residents. This study simulated pollutant concentration variations for one day in a bedroom in Nanjing under different supply fresh air supply modes based on Modelica. The indoor air quality, indoor temperature fluctuation, and fresh air energy consumption were analyzed. The main findings and conclusions are as follows:

(1) When the fixed window-opening ratio was 25% (0.3 m²), the PM$_{2.5}$ concentration exceeded the good category was 2.59 h but did not exceed the moderate category; the ozone concentration did not exceed the good category. When the window-opening ratio increased to 50% in summer, the energy consumption increased by a factor of 2.16. When the window-opening ratio increased to 75% and 100%, the air conditioner could not maintain the indoor temperature within the setting range. The study findings recommend using a 25% window-opening ratio during cooking (approximately 0.3 m²) in summer.

(2) As the outdoor PM$_{2.5}$ concentration is too high in winter in Nanjing, indoor air pollution is aggravated by opening the windows. Moreover, the fresh air energy consumption significantly increases because of the large temperature difference between indoor and outdoor air. Therefore, natural ventilation is not recommended in winter.

(3) The fresh air energy consumption of the automatic-control window-opening ratio was only 0.48 kW·h, which was one-fifth that of the 25% fixed window-opening ratio. Therefore, the fresh air supply mode of the automatic-control window-opening ratio is better than that of the fixed window-opening ratio in summer.

(4) In both summer and winter, the fresh air system of the total heat exchanger can improve indoor air quality. In summer, the total energy consumption of fresh air was 1.30 kW·h, which was 0.51 times that of the 25% window-opening ratio and 2.7 times that of the automatic-control window-opening ratio.

Therefore, this study recommends using a fresh air system in winter and natural ventilation of the automatic-control window-opening ratio in summer to provide fresh air to the bedroom. It is only 19.3% of fresh air energy consumption of 25% fixed window-opening ratio and 38.1% of fresh air energy consumption of using fresh air equipment in summer. In the whole summer (90 days), the fresh air supply method of automatic-control window-opening ratio can save 196.1 kW·h and 72.5 kW·h than 25% fixed window-opening ratio and fresh air equipment, respectively. In winter, the fresh air energy consumption of fresh air equipment is 6.9% of the 25% fixed window-opening ratio. The use of natural ventilation in Nanjing in winter not only significantly increases fresh air energy consumption but also worsens the indoor air quality in poor outdoor environments. The 24-hour indoor average PM$_{2.5}$ concentration using natural ventilation with a 25% fixed window-opening ratio is approximately 4.9 times that using fresh air equipment. Therefore, natural ventilation is not recommended in Nanjing in winter.

This study evaluates the effects of different ventilation modes on indoor air quality and fresh air energy consumption when the bedroom is occupied for 24 h under specific conditions (such as during the COVID-19 pandemic). However, the relationship between fresh air energy consumption and indoor air quality in bedrooms, considering variations in occupation time, needs to be further investigated.

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.
Acknowledgments

This study was supported financially by the National Key R&D Program of China (No. 2016YFC0701402).

References

[1] WHO Regional Office for Europe. Economic cost of the health impact of air pollution in Europe: Clean air, health and wealth, 2015.

[2] C. Schweizer, R.D. Edwards, L. Bayer-Oglesby, W.J. Gauderman, V. Ilacqua, M.J. Cutler, A state-of-the-art review on indoor air pollution and strategies for indoor air pollution control, Chemosphere 262 (2021) 128376. https://doi.org/10.1016/j.chemosphere.2020.128376.

[3] W.S. Dols, B.J. Polidoro, CONTAM User Guide and Program Documentation. 2006, The Modelica Association, Vienna, Austria, 2006, pp. 431-440.

[4] Ministry of Housing Urban-Rural Construction of the People’s Republic of China. Design code for heating ventilation and air conditioning of civil buildings: A review, Ashrae Transactions 107 (2) (2001) 619–628

[5] B. Chenari, J. Dias Carrilho, M. Gameiro da Silva, Towards sustainable, energy-efficient houses: A literature review, Build. Environ. 131 (2018) 231–241

[6] F. Xu and Z. Gao Energy & Buildings 257 (2022) 111805

[7] R. Sangi, D. Müller, Dynamic modelling and simulation of a slinky-coil horizontal ground heat exchanger using Modelica, Journal of Building, Engineering 43 (2021) 103140, https://doi.org/10.1016/j.proeng.2021.103140.

[8] Y. Fu, W. Zuo, M. Gao, Energy & Buildings 257 (2022) 111805

[9] R. Sangi, D. Müller, Dynamic modelling and simulation of a slinky-coil horizontal ground heat exchanger using Modelica, Journal of Building, Engineering 43 (2021) 103140, https://doi.org/10.1016/j.proeng.2021.103140.

[10] R. Al-Waked, M. Nasif, N. Groenhout, L. Partridge, Natural ventilation of residential building Atrium under fire scenario, Case Studies in Thermal Engineering 26 (2021) 101041, https://doi.org/10.1016/j.csite.2021.101041.

[11] S. Park, Y. Choi, D. Song, E.K. Kim, Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building, Sci. Total Environ. 789 (2021) 147764, https://doi.org/10.1016/j.scitotenv.2021.147764.

[12] M. Wetter, Multizone Airflow Model in Modelica, in: Modelica Conference 2006, The Modelica Association, Vienna, Austria, 2006, pp. 431-440.

[13] F.Y. Xiao, L. Wang, M. Yu, H. Liu, J. Liu, Effects of source emission and window opening on indoor winter indoor particle concentrations in the severe cold region of China, Build. Environ. 144 (2018) 23–33, https://doi.org/10.1016/j.buildenv.2018.08.001.

[14] F. Stazi, F. Fabian, G. Adamkiewicz, J.I. Levy, Simulating indoor concentrations of NO2 and PM2.5 in multifamily housing for use in health-based intervention modeling, Indoor Air 22 (1) (2012) 12–23, https://doi.org/10.1111/j.1600-0668.2011.00742.x.

[15] W.S. Dols, S.J. Emmerich, B.J. Polidoro, Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation, Build. Simul. 9 (4) (2016) 469–479, https://doi.org/10.1007/s12273-012-0179-7.

[16] B. Chenari, J. Dias Carrilho, M. Gameiro da Silva, Towards sustainable, energy-efficient houses: A literature review, Build. Environ. 131 (2018) 231–241

[17] F. Xu and Z. Gao Energy & Buildings 257 (2022) 111805

[18] T. Granot, M.R. Raychaudhuri, Compilation of tables of surface deposition velocities for NO2 and NO2 for a range of indoor surfaces, Atmos. Environ. 38 (4) (2004) 533–547, https://doi.org/10.1016/j.aegeo.2003.10.010.

[19] U.S. Environmental Protection Agency, Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI), 2018.

[20] Ministry of Ecology, Tectonic, Regulation and Environmental Quality Index, Environment of People’s Republic of China, Beijing, 2012.

[21] S.J. Emmerich, Validation of multizone IAQ modeling of residential-scale buildings: A review, Ashrae Transactions 107 (2) (2001) 619–628.