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Lin, Yin, Yuan, Xingping, Yang, Wei, Chan, Melissa and Tian, Lin (2023) Impact of outdoor particulate matter 2.5 pollution on natural ventilation energy saving potential in office buildings in China. Journal of Building Engineering, 76. ISSN 2352-7102

Impact of Outdoor Particulate Matter 2.5 Pollution on Natural Ventilation Energy Saving Potential in Office Buildings in China

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Abstract

Natural ventilation improves building energy performance and indoor air quality, but its potential is hindered by outdoor pollution. This paper aims to evaluate the impact of outdoor Particulate Matter 2.5 ($PM_{2.5}$) pollution on natural ventilation energy saving potential in office buildings in China. Firstly, a typical office building in five representative cities across all climatic regions was designed. Secondly, related weather data were obtained and preprocessed. Thirdly, a computer model was developed under the EnergyPlus environment with smart window ventilation control, space temperature reset using adaptive thermal comfort model, and a validated pollution transportation model that calculates the indoor $PM_{2.5}$ concentration. The computer model was applied to three air-conditioning systems, i.e., constant air volume (CAV), variable air volume (VAV), and variable refrigerant flow (VRF) with three evaluation indices. The results show that the natural ventilation hours rate with/without considering the outdoor $PM_{2.5}$ concentration level were 15%~55% and 28%~67%, respectively. Energy savings varied across regions, with mild regions having the highest potential and cold regions having the least. CAV demonstrates the highest energy savings, followed by VAV and VRF, except in Guangzhou where VAV performs the worst. This study contributes to understanding the impact of outdoor pollution on natural ventilation potential and provides practical insights for energy-saving strategies in office buildings. Its originality lies in the evaluation methodology, comprehensive approach, sophisticated computer model, comparative analysis of air-conditioning systems, and practical implications for energy-savings. The research outcomes can guide building facility engineers in implementing ventilation control strategies while maintaining indoor thermal

comfort.

KEYWORDS

Natural Ventilation; Energy Saving Potential; $PM_{2.5}$ Pollution; Office Building; Air-Conditioning Systems

Abbreviations

ABEC = Annual Building Energy Consumption

AQI = Air Quality Index

CADR = Clean Air Delivery Rate

CAV = Constant Air Volume

COP = Coefficient Of Performance

EMS = Energy Management System

HV = Hybrid Ventilation (HV1 considers outdoor air temperature only; HV2 takes into account both outside air temperature and $PM_{2.5}$ concentration)

HVAC =Heating, Ventilation and Air-conditioning

IAQ = Indoor Air Quality

NV = Natural Ventilation

MV = Mechanical Ventilation

$PM_{2.5}$ = Particulate Matter 2.5

SHGC = Solar Heat Gain Coefficient

TMY = Typical Meteorological Year

VAV = Variable Air Volume

VRF = Variable Refrigerant Flow

Nomenclature

A = Coefficient, set as 1

A_{floor} = Floor area, m^2

A_{open} = Opening area, m^2

$A_{open,max}$ = Maximum operable area, taken as 8% of the floor area of the room where it is located, which is equivalent to 41% of the area of the outer window, with a total area of 58 m^2

A_s = Deposition surface area, m^2

B = Coefficient, set as 0

C = Coefficient, set as 0

C_{cutoff} = $PM_{2.5}$ concentration when the pollution source stops diffusion, ppm

C_D = Discharge coefficient for opening, dimensionless

CF = Crack factor, dimensionless

$C_f(t)$ = $PM_{2.5}$ concentration, ppm

$Cost_{MV}$ = Utility cost under mechanical ventilation mode, ¥

$Cost_{NV}$ = Utility cost under natural ventilation mode (HV1 or HV2), ¥

C_Q = Flow coefficient, taken as 0.001kg/(s·m) for windows fully closed and 0.01kg/(s·Pa) for the opaque envelope

C_T = Temperature correction coefficient, applied to opaque envelope only, dimensionless

C_w = Opening effectiveness, dimensionless

D = Coefficient, set as 0

$Energy_{MV}$ = Energy consumption under mechanical ventilation mode, kWh

$Energy_{NV}$ = Energy consumption under natural ventilation mode (HV1 or HV2), kWh

F_G = Present occupancy status, dimensionless

F_R = Pollution removal schedule, dimensionless.

$F_{schedule}$ = Opening status, set according to the time table, dimensionless

g = Gravitational acceleration, taken as 9.87 m/s^2

$G_f(t)$ = Design $PM_{2.5}$ generation rate, m^3/s

k_d = Deposition rate, taken as 1/s

m = Element multiplier, dimensionless

m_p =Increased amount of $PM_{2.5}$ emitted by human activities, kg/s

n = Flow exponent, taken as 0.598

N_{NV} = Total number of hours suitable for natural ventilation during occupied, hr

N_{OCC} = Annual total occupied hours, equal to 3814 hrs

P = Atmeric pressure, taken as 97.665 kPa

Q = Ventilation mass rate, kg/s

q_{design} = Design infiltration volume flow rate, set as 4 $m^3/(m^2 \cdot h)$

Q_{NV} = Total ventilation rate, kg/s

Q_{stack} = Ventilation rate by the stack, kg/s

Q_{wind}= Ventilation rate by wind, kg/s

R_g = Universal gas constant, taken as 8.314 J/mol·K

$S_f(t)$ = Indoor pollutants generation/removal intensity, m^3/s

T = Air temperature, K

t_c = Time constant for the pollutant generation rate to reach 0.37 of the original generation rate, second

$T_{cooling,newsetpoint}$ = New cooling indoor temperature setpoint based on adaptive thermal comfort model, ºC

T_{in}= Indoor air temperature, ºC

T_{MRT} = Mean radiant temperature, ºC

T_o = Average value of the outdoor temperature for the previous 30 days, ºC

$T_{OP,setpoint}$ = Operative temperature setpoint, ºC

T_{out} = Outdoor air temperature, ºC

v = Local wind speed, m/s

v_d = Deposition velocity, m/s

V_z = Zone volume, m^3

Greek symbols

ρ_0 = Air density at reference temperature of 20^o C, taken as 1.20 kg/m^3

v = Air kinematic viscosity, in m^2/s

v_0 = Air kinematic viscosity at reference temperature and atmospheric pressure

ΔH_{NPL} = The height from midpoint of lower opening to neutral pressure level, in m

ΔP = Air pressure difference between the indoor and outdoor, in Pa

Δt = Temperature difference between the indoor and outdoor， in °C

1. Introduction

With the rapid increase of population density and aging population in large cities, the health burden caused by air pollution is gradually increasing [1]. In 2015, the number of deaths caused by $PM_{2.5}$ pollution in the Beijing-Tianjin-Hebei region of China reached 193,800, leading to health and economic losses of over 35.934 billion RMB, which was about 0.7% of its gross domestic product [2]. Meanwhile, the increase in outdoor $PM_{2.5}$ concentration also leads to an increase in building energy consumption which is already high. It was shown that every 1 μg/m^3 increase in $PM_{2.5}$ concentration will lead to an increase in residential electricity consumption by 0.145kWh/day per household [3].

In 2018, building operational energy consumption accounts for 46.6% of the lifecycle building energy consumption and 21.7% of the national energy consumption in China [4]. As a big proportion of electricity generation is through coal-fired, building energy consumption leads to a rapid increase in $PM_{2.5}$ pollution and CO_2 emission [5]. Therefore, it is urgent to reduce building energy consumption and air pollution. As an effective way to improve the building energy performance and indoor air quality, natural ventilation has received wide attention.

Over the years, many researchers have conducted studies on natural ventilation energy saving potential. Tong et al. [6] evaluated the natural ventilation energy saving potential for office buildings of 76 Chinese cities during 2015 using natural ventilation (NV) hours and predicted an average NV hours of 2324 out of 8760 h/year and 8%-78% of cooling energy reduction. For 35 big cities in China, a 43 GWh energy saving loss out of 112 GWh in 2015 was projected due to air pollution. Chen et al. [7] investigated the impact of three major outdoor air pollutants, $PM_{2.5}$, PM_{10} and ozone, on the use of natural ventilation in 12 major cities in the United States. It was shown that the natural ventilation hours could be reduced by 5-70% due to outdoor air pollution, especially outdoor $PM_{2.5}$ concentration. Song et al. [8] quantified the impact of outdoor air pollution on natural ventilation energy saving potential and found a loss of annual cooling energy saving potential of 9.0 kWh/m^2 at the city scale in London. Chen et al. [9] investigated the natural ventilation hours of 60 cities around the world and found the subtropical highland climate was most favorable for natural ventilation. Oropeza-Perez et al. [10] evaluated the energy savings of natural ventilation for 27 common cases of dwellings in Mexico and predicted an average aggregated saving potential of 54.5% of electric cooling demand in 2008. Ji et al. [11] studied the trend of natural ventilation potential in 74 cities in China from 2014 to 2019 and found the reduction on the natural ventilation hours was highest in the cold region (with 54.9%) and lowest in the mild region (with 20.3%). Chen et al. [12] conducted research on the regional differences of natural ventilation energy saving potential affected by outdoor air pollution. They found that the impact in urban/suburban areas was higher than rural areas and it was mostly affected by the outdoor $PM_{2.5}$ pollutants. More studies on the assessment of energy saving potential of natural ventilation in recent decades are listed in Table 1.

Based on the above literature review, it can be seen that previous studies have provided valuable information on the hours available for natural ventilation, energy consumption and operating cost reduction. However, there are some research gaps that need to be addressed in order to maximize or more accurately evaluate the energy saving potential. First, the assumption on the window opening area could be improved to maximize energy savings. Some studies used fixed window opening area for natural ventilation [13], or adopted a stochastic model for window opening behaviors [14], or assumed a linear relationship between increased window opening area with the increase of outdoor air temperature [15]. Some other studies did not even consider the window opening area

[6,7,12,16]. In fact, the use of natural ventilation should firstly consider whether cooling or heating is needed, based on which then adjust the window opening area in order to maximize the energy saving. Secondly, the application of adaptive thermal comfort model in the evaluation of natural ventilation energy savings could be improved. For example, the adaptive thermal comfort model was used to only determine the upper limit of the outdoor air temperature, without considering the indoor operative temperature [6, 17]. Thirdly, the indices to evaluate the energy saving potential of natural ventilation could be improved. For example, the use of NV hours only tells the maximum number of hours available for natural ventilation [6,7,16,17], and the energy consumption reduction savings typically do not consider the actual operation of different types of air-conditioning system and cost savings. Lastly, most of the studies did not ensure minimum fresh air requirement during the occupied hour during natural ventilation, which potentially leads to an overestimation of its energy saving potential.

Table 1 Relevant Studies on Natural Ventilation Energy Saving Potential

Building type	Climatic region	Data source	Natural ventilation period	Research method	Energy saving potential assessment method	Conclusion	Ref
High-rise building	Six populated cities in Six climatic zones in USA	Hourly surface and upper air meteorological data and land cover data in 2011	$T_{out,dew}^{1}\leq17$℃, 12.8℃$\leq T_{out}^{2}\leq$ Upper limit of the adaptive thermal comfort model, V_{out}^{3} is determined by empirical equation, $V_{in}^{4}<0.8$m/s	Create a boundary layer meteorological model to study the vertical local climate profile	Estimate the vertical Natural Ventilation (NV) hours from the surface up to 300 m above the ground for each city	NV hours are negatively correlated with building heights in all cities except Miami, which has an almost uniform vertical distribution	[17]
Office building	14 representative cities in the United States and Canada	Meteorological data for a typical year, 2050 and 2080	11.9℃$\leq T_{out}^{2}\leq$ 21.6℃; 21℃$\leq T_{in,cooling}^{5}\leq$28℃, 18℃$\leq T_{in,heating}^{6}\leq$ 25℃	Hybrid ventilation model based on adaptive thermal comfort, stochastic window operation model	Simulated energy consumption under hybrid ventilation mode compared with mechanical ventilation mode (benchmark consumption)	NV availability gradually decreases with climate change. The higher cooling energy consumption due to climate change can be greatly reduced by adopting suitable NV, but the stochastic model shows that the inefficient use of windows will lead to low energy saving rate	[14]
Medium office building	76 cities in China	Chinese standard weather data (CSWD) and hourly Air quality index (AQI) data from August 2014 to August 2015	$T_{out,dew}^{1}\leq18$℃, 12.8℃$\leq T_{out}^{2}\leq$ Upper limit of the adaptive thermal comfort model, AQI≤100	Use EnergyPlus to simulate annual energy consumption and calculate carbon emissions	Calculate the NV hours and energy consumption for 35 major cities based on energy consumption data of newly constructed office buildings as benchmarks	After considering the 43 GWh energy saving loss caused by severe air pollution, the total NV energy saving potential of office buildings in 35 major Chinese cities in 2015 was 112 GWh	[6]

Office building	California's Five Largest Metropolitan Areas	Hourly weather data and outdoor $PM_{2.5}$ data in ten years	10℃≤T_{out}[2]≤26℃, $PM_{2.5,out}$[7]≤12μg/m³	Considered the air filter in the ventilation system and window opening area varied with outdoor air temperature	Using mechanical ventilation mode as the benchmark model; simulated the yearly energy consumption with/without considering $PM_{2.5}$ concentration	Without considering $PM_{2.5}$ concentration, NV leads to 25~80% reduction in heating, ventilation and air-conditioning (HVAC) system energy consumption; $PM_{2.5}$ reduces the energy saving potential to 20-60%	[15]
Apartment	Five Cities with Typical Climates in China	Typical annual meteorological data, fixed outdoor CO_2 concentration and outdoor $PM_{2.5}$ data in 2016	18℃≤T_{out}[2]≤ 26℃, $PM_{2.5,in}$[8]≤35μg/m³, $CO_{2,in}$[9]≤1000ppm	Consider the effect of different air filters in the ventilation system by using the clean air delivery rate (CADR) for evaluation	Simulate the energy consumption of apartment buildings in 2016 under five ventilation modes with/without air filter	Fully natural ventilation mode leads to the lowest cost but cannot guarantee the ventilation rate during 27%~79% of the time period; Fully mechanical ventilation mode leads to good indoor air quality (IAQ) and double the cost under fully natural ventilation mode	[13]
Medium office building	Seven Cities with Typical Climates in China	Typical year weather data (CSWD)	T_{in}[10] > T_{out}[2] (Two different indoor air humidity thresholds (70% and 80%) are considered)	Proposed an energy consumption "pre-assessment" tool, analyzing 6 ventilation scenarios in 100 cities under 5 standards, including nighttime decontamination	Calculate the NV hours, building cooling energy consumption and public utility cost	Relative humidity is an important factor affecting NV energy saving, and it is necessary to use mechanical ventilation to ensure the minimum fresh air rate. The NV energy saving potential of mild weather region is the highest	[16]
Small commercial building	12 cities with typical climate in the United States	Hourly data of outdoor pollutants ($PM_{2.5}$, PM_{10}, ozone) and typical annual meteorological data in five years	$PM_{2.5,out}$[7]≤12μg/m³, $PM_{10,out}$[10]≤150μg/m³, $O_{zone,out}$[11]≤0.07ppm, 19℃≤T_{out}[2]≤26℃, V_{out}[3]≤7m/s	Investigated the effects of three major outdoor air pollutants on the utilization of natural ventilation in 12 major U.S. cities	Calculate the NV hours with/without considering the outdoor air pollutants	Reduction of NV hours due to outdoor air pollutants ranges from 5% to 70%; $PM_{2.5}$ pollutant has the highest impact on the NV hours while PM_{10} pollutant has negligible impact.	[7]

[1]Outside dewpoint temperature.

[2]Outside drybulb temperature.

[3]Outside air velocity.

[4]Inside air velocity.

[5]Indoor cooling temperature setpoint.

[6]Indoor heating temperature setpoint.

[7]Outside $PM_{2.5}$ concentration.

[8]Inside $PM_{2.5}$ concentration.

[9]Inside CO_2 concentration

[10]Inside air temperature.

[11]Outside PM_{10} concentration.

[12]Outside Ozone concentration.

To address the above identified research gaps, this study aims to evaluate the impact of outdoor $PM_{2.5}$ pollution on natural ventilation energy saving potential of office buildings in China. This is achieved through the integration of various models into a computer model. Specifically, a window ventilation opening model was developed, which considers the indoor-outdoor temperature difference and outdoor $PM_{2.5}$ concentration. A thermal comfort model was employed to calculate the indoor operative temperature for indoor air temperature reset. A pollution transportation model was validated with experimental results to calculate the indoor $PM_{2.5}$ concentration. In addition, multiple evaluation indices were used to assess natural ventilation energy saving potential while ensuring the minimum fresh air flow rate during the occupied hours. Three air conditioning systems, i.e., variable refrigerant flow (VRF), constant air volume (CAV), and variable air volume (VAV) systems are accessed. The computer model was developed under the EnergyPlus environment to perform building energy simulation. Typical meteorological weather (TMY) data, Chinese standard weather data (CSWD), and hourly weather data from 2016-2020 were adopted for comparative analysis. The building energy savings and cost savings of natural ventilation as well as NV hours were provided.

2. Method

The research framework of the study includes four steps (Figure 1). The first step involves the selection of five representative cities across typical climatic regions in China. The second step is the preprocessing of weather data of the selected cities, including the typical meteorological weather (TMY) data, Chinese standard weather data (CSWD), and hourly weather data from 2016-2020. In the third step, the processed weather data were then used as inputs to the computer model developed under the EnergyPlus environment, which includes the development of building model, ventilation model, thermal comfort model, pollution transportation model (validated with experimental results), and ventilation control strategies with system configuration. Finally, the outcomes from the computer program were used to evaluate the natural ventilation potential.

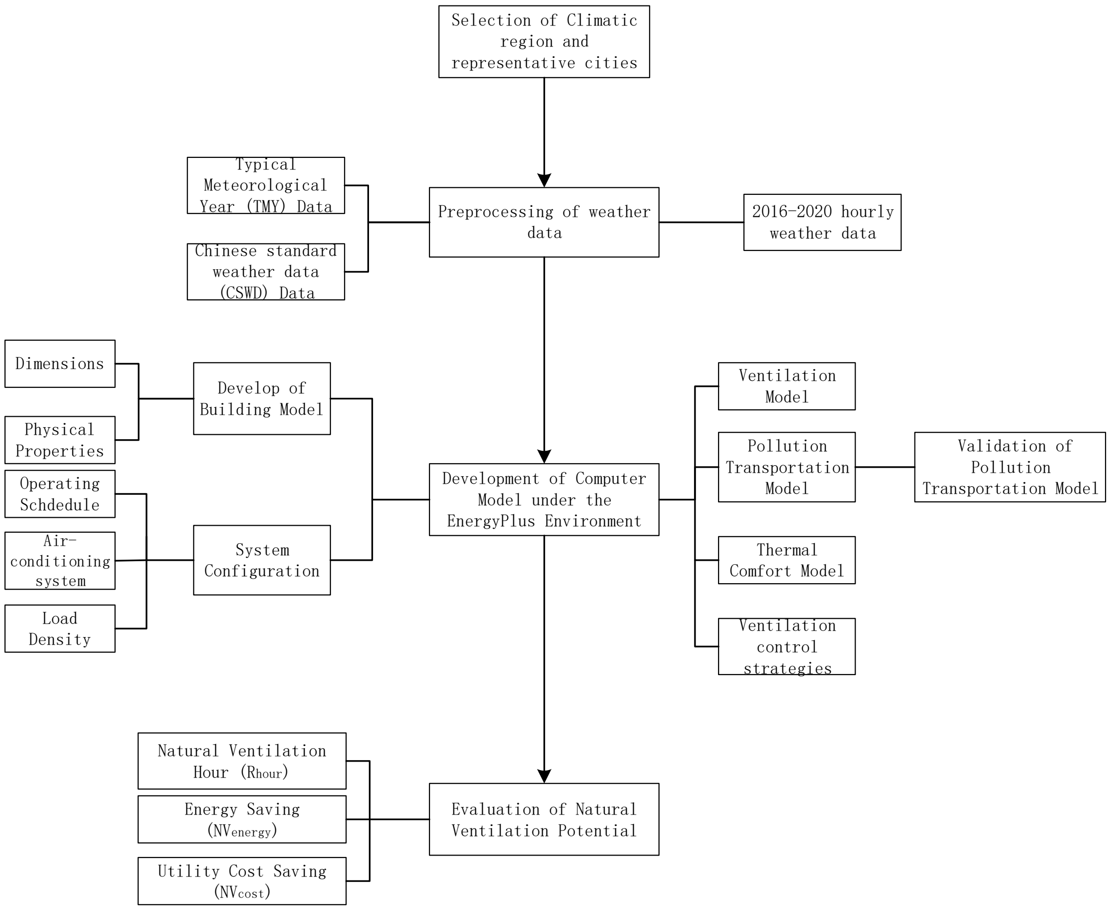

Figure 1. Research framework of the study

2.1 Climatic region and representative cities

To provide a comprehensive understanding of natural ventilation potential, it is necessary to select cities from various climatic regions. According to GB 50352-2019 [18], five representative major cities, including Harbin, Beijing, Shanghai, Guangzhou and Kunming, were selected to evaluate the NV energy saving potential in the server cold region, cold region, hot summer and cold winter region, hot summer and warm winter region, and mild regions in China (Figure 2). Those cities are chosen because 1) they cover all the climatic regions in China, and 2) they are municipalities or capital cities that can best represent their respective regions.

Figure 2. Geographical locations and climate zones of the representative cities

2.2 Data source and preprocessing

Accuracy of the weather data is very important in the evaluation of natural ventilation performance, as the availability of natural ventilation and building energy consumption are highly affected by the weather data. Therefore, only the weather data from reputable official website were adopted. The data used in the study include hourly typical meteorological year (TMY) data with outdoor $PM_{2.5}$ concentration, hourly meteorological data and outdoor $PM_{2.5}$ concentration data during 2016-2020, and Chinese Standard Weather Data (CSWD) with typical outdoor $PM_{2.5}$ concentration data during 2016-2020. The CSWD data were downloaded from the EnergyPlus official website [19], and the hourly data from 2016 to 2020 were downloaded from Renewable Energy Data Explorer website [20]. The hourly typical year outdoor $PM_{2.5}$ concentration data was obtained based on the historical $PM_{2.5}$ data during 2016-2020 downloaded from the official website of China National Environmental Monitoring

Centre [21]. Due to technical failures of monitoring stations and large data sample size, there were a certain amount of missing data (less than 1.4%) which were supplemented using linear interpolation. The months that have the average concentration closest to the monthly average concentration of 2016-2020 were selected as the typical months for simulation. The outdoor $PM_{2.5}$ concentration level of 35μg/m^3 was applied as the upper limit for window opening according to the Ambient Air Quality Standards [22]. Figure 3 presents the monthly average outdoor temperature (solid line) and outdoor $PM_{2.5}$ concentration (dash line) in a typical year. The highest temperature can be observed in the hot summer and warm winter region, which is in the range of 13^{o} C ~28 ^{o} C. The greatest fluctuation in temperature (-18^{o} C ~22^{o} C) occurred in the severe cold region. In the mild region, the temperature is in the range of 8^{o} C ~20^{o} C. Low $PM_{2.5}$ concentration level can be observed during the cooling season (from May to October) and high in the heating season (from November to April). The greatest fluctuation range (16 μg/m^3 ~95 μg/m^3) can be observed in Harbin. The yearly $PM_{2.5}$ concentration level is highest in Beijing (51 μg/m^3), followed by Harbin (45 μg/m^3), Shanghai (37 μg/m^3), Guangzhou (32 μg/m^3), and Kunming (26 μg/m^3). The typical year $PM_{2.5}$ concentration of each city is approximately equal to the average $PM_{2.5}$ concentration during 2016 ~ 2020.

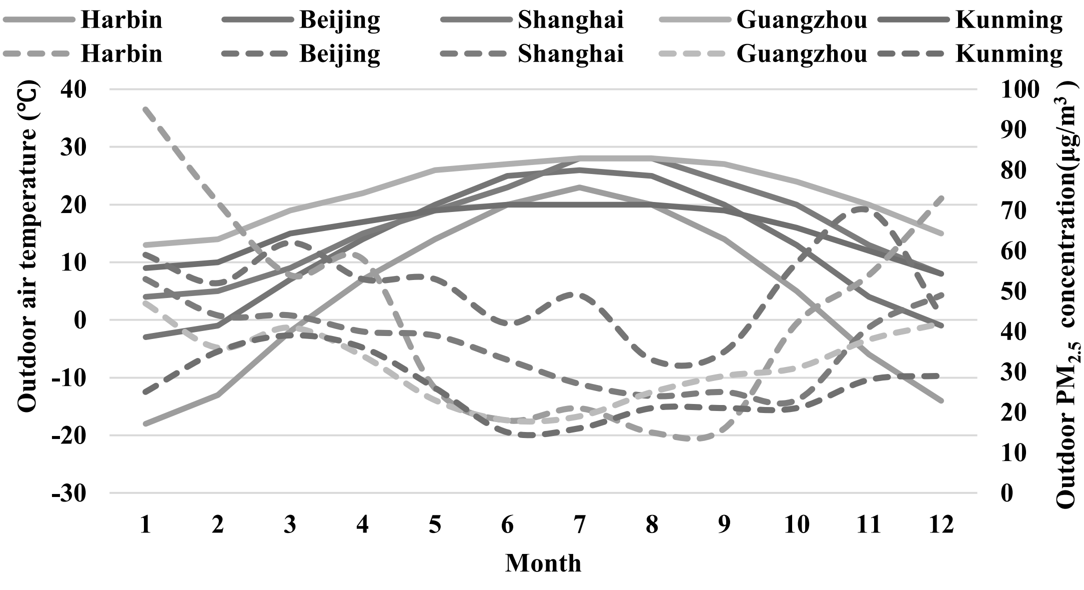

Figure 3. Monthly average outdoor temperature (solid line) and outdoor $PM_{2.5}$ concentration (dash line) in a typical year

2.3 Model description

2.3.1 Building description

To assess building performance, it is essential to select a representative office building in China. Therefore, a typical three-story office building (Figure 4) facing due south, with a total construction area of 2197.92 m^2 and a height of 13.6 m, was designed based on the building model database from the Design Standards for Energy Conservation of Public Buildings [23]. The overall window-to-wall area ratio of the building was 0.24, and the airtightness level of the outer doors and windows was 6 [23]. This study focuses on the third floor with dimensions of 48.2 m ×15.2 m ×4 m. Detailed information on window-to-wall ratio of the third floor and the physical properties of the building envelope is presented in Tables 2 and 3.

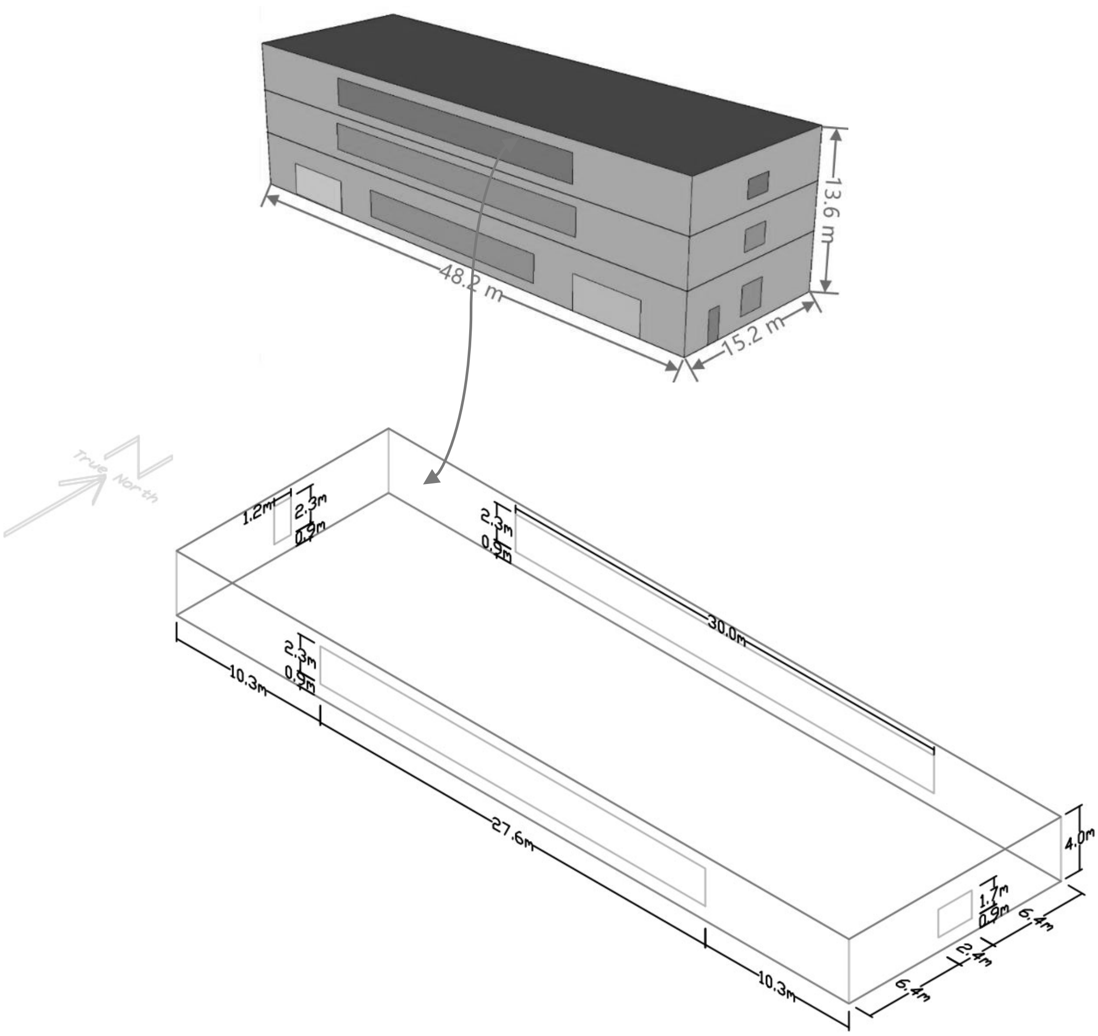

Figure 4 Building model

Table 2 Window-to-wall ratio of the third floor

	East	South	West	North
Window area (m^2)	4.176	64.584	2.808	70.2
External wall area (m^2)	60.8	192.8	60.8	192.8
Design window-to-wall ratio (-)	0.07	0.33	0.05	0.36
Required by [18]	≤0.6 for severe cold region and ≤0.7 for other region			

Table 3 Physical properties of the building envelope

Region	City	Value	U-Value of the Roof [W/m^2.K]	U-Value of the Wall [W/m^2.K]	U-Value of the Window [W/m^2.K]	SHGC*
Severe cold	Harbin	Require	≤0.28	≤0.38	≤2.2	——
		Design	0.235	0.245	1.5	0.54
Cold	Beijing	Require	≤0.45	≤0.50	≤2.4	≤0.48
		Design	0.398	0.458	1.8	0.44
Hot summer and cold winter	Shanghai	Require	≤0.40	≤0.60	≤2.6	≤0.40
		Design	0.358	0.514	2.4	0.30
Hot summer and warm winter	Guangzhou	Require	≤0.50	≤0.80	≤3.0	≤0.35
		Design	0.429	0.741	2.4	0.30
Mild	Kunming	Require	≤0.50	≤0.80	≤3.0	≤0.40
		Design	0.499	0.741	2.4	0.30

* Solar Heat Gain Coefficient

2.3.2 System configuration

A computer program was developed using EnergyPlus software, which can model the heat transfer process, infiltration, hybrid ventilation, mechanical ventilation and pollution transportation through the building envelope. At the same time, the control strategies can be customized through the Energy Management System (EMS) Module [24]. The HVAC system operation schedule, indoor air temperature setpoint, load density as well as system selection greatly affect the building energy consumption. According to the Office Building Design Standard [25], the indoor air temperature was recommended to maintain in the range of 26℃ ~ 28℃ with relative humidity below 70% and wind speed less than 0.3 m/s in summer; the indoor air temperature was recommended to maintain in the range of 18℃ ~ 20℃ with no control on the relative humidity and wind speed less than 0.2 m/s in winter. According to [23], the HVAC system operation schedule is 7:00 AM to 6:00PM, Monday to Friday, not including public holidays. The office hour is 8:00 AM to 6:00PM. The occupant density, minimum fresh air volume, lighting density, the equipment load density are 10 m^2/person, 30 m^3/h per person, 9 W/m^2, and 15W/m^2, respectively. The yearly working hours is 2695h, and HVAC system operation hours is 3184h. Table 4 lists the detailed operation schedule and temperature setpoint (when the adaptive thermal comfort model is not applicable) for the equipment systems.

Table 4. Operation schedule of each system in the building

Time (h)	Temperature setpoint (℃)				Working condition			
	Workday		Holiday		Occupancy rate (%)	Lighting (%)	System operation*	Electrical equipment usage rate(%)
	Cooling	Heating	Cooling	Heating				
1	37	5	37	5	0	0	0	0
2	37	5	37	5	0	0	0	0
3	37	5	37	5	0	0	0	0
4	37	5	37	5	0	0	0	0
5	37	5	37	5	0	0	0	0
6	37	12	37	5	0	0	0	0
7	28	18	37	5	10	10	1	10
8	26	20	37	5	50	50	1	50
9	26	20	37	5	95	95	1	95
10	26	20	37	5	95	95	1	95
11	26	20	37	5	95	95	1	95
12	26	20	37	5	80	80	1	50
13	26	20	37	5	80	80	1	50
14	26	20	37	5	95	95	1	95
15	26	20	37	5	95	95	1	95
16	26	20	37	5	95	95	1	95
17	26	20	37	5	95	95	1	95
18	26	20	37	5	30	30	1	30
19	37	18	37	5	30	30	1	30
20	37	12	37	5	0	0	0	0
21	37	5	37	5	0	0	0	0
22	37	5	37	5	0	0	0	0
23	37	5	37	5	0	0	0	0
24	37	5	37	5	0	0	0	0

*"0" refers to "OFF" and "1" refers to "ON"

Three air-conditioning system, i.e., variable air volume (VAV), constant air volume (CAV), and variable refrigerant flow (VRF) +fresh air unit, were considered in the simulation. Air cooled reciprocating chiller was adopted for all the systems except the

VRF system. The coefficient of performance (COP) of the air cooled chilled as well as the VRF system under nominal cooling conditions in Harbin, Beijing, Shanghai, Guangzhou, and Kunming were set to be 2.6, 2.6, 2.7, 2.8, and 2.6, respectively [23]. Gas-fired boiler was adopted for heating with an efficiency of 0.9[23].

2.3.3 Ventilation model

The ventilation model was developed to calculate the air infiltration from outdoor to the indoor, which is important to determine the amount of free cooling. Both mechanical ventilation (fresh air intake is fully from air infiltration and mechanical system) and hybrid ventilation (natural ventilation and mechanical system work alternatively) were considered in this study. The air infiltration volume flow rate under mechanical ventilation mode can be calculated by [26]：

$$V_{infiltration} = q_{design} F_{schedule} [A + B|(T_{zone} - T_{out})| + CV_{wind} + DV_{wind}^2] \quad (1)$$

where q_{design} is the design infiltration volume flow rate, set as 4 $m^3/(m^2 \cdot h)$ [27]; the A,B,C, and D are coefficients, set as 1,0,0, and 0, respectively [27].

The infiltration under natural ventilation mode can be calculated using the crack method:

$$Q = CF * C_T * C_Q (\Delta P)^n \quad (2)$$

where C_Q is the flow coefficient, taken as 0.001kg/(s·m) for windows fully closed and 0.01kg/(s·Pa) for the opaque envelope [13]; n is the flow exponent, taken as 0.598 [13]. The temperature correction coefficient can be calculated by the following equation [26]:

$$C_T = \left[\frac{\rho_0}{\rho}\right]^{n-1} \left[\frac{v_0}{v}\right]^{2n-1} \quad (3)$$

where ρ_0 is the air density at reference temperature of 20° C, taken as 1.20 kg/m^3.

The natural ventilation through the window opening can be calculated by [28]:

$$Q_{NV} = \sqrt{(Q_{stack})^2 + (Q_{wind})^2} \quad (4)$$

$$Q_{wind} = \rho * C_w * A_{open} * F_{schedual} * \mathrm{v} \quad (5)$$

$$Q_{stack} = \rho * C_D * A_{open} * F_{schedual} * \sqrt{2 * g * \Delta H_{NPL} \frac{(|T_{in} - T_{out}|)}{T_{in}}} \quad (6)$$

The window opening area can be calculated by [28]:

$$A_{open} = \begin{cases} A_{open,\max} & , \quad |\Delta t| < 5℃ \\ (1.7 - 0.14 * \Delta t) * A_{open,max} & , 5℃ \le |\Delta t| < 10℃ \\ 0.3 * A_{open,max} & , \quad |\Delta t| \ge 10℃ \end{cases} \quad (7)$$

where $A_{open,max}$ is the maximum operable area, taken as 8% of the floor area of the room where it is located, which is equivalent to 41% of the area of the outer window, with a total area of 58 m^2 [23,29].

2.3.4 Pollution transportation model

The pollution transportation model was developed to help determine the indoor $PM_{2.5}$ concentration level. The main factors affecting indoor $PM_{2.5}$ concentration include ventilation process, indoor source diffusion process, sedimentation process, re-suspension process, and removal process [30]. The ventilation process has been discussed in section 2.3.4. The indoor source diffusion process includes personnel activities and printing for non-smoking area [30]. Field measurements from an office space with an area of 80 m^3 have shown that the activities of a single person can cause an increase of 0.004 $\mu g/(m^3 \cdot s)$ in $PM_{2.5}$ pollution [31]. Szigeti et al. [32] found that printing services have a negligible impact on indoor $PM_{2.5}$ concentration. No indoor air purification device was considered and a sedimentation rate of 0.39/h was recommended by Ozkaynak et al. [33]. Lai et al. [34] confirmed that the sedimentation rate of the horizontal downward smooth surface was almost 0, so only the $PM_{2.5}$ removal rate of the floor surface was considered.

The cutoff concentration model, decay source model, surface sink model, and zone sink model are given in equations (8a-d) [26]:

$$S_f(t) = \begin{cases} G_f(t) F_G (1 - \frac{C_f(t)}{C_{cutoff}}), & C_f < C_{cutoff} \\ 0, & C_f \ge C_{cutoff} \end{cases} \quad (8a)$$

$$S_f(t) = G_f(t) F_G exp(-t/t_c) \quad (8b)$$

$$S_f(t) = v_d A_s m C_f(t) * 1.0 * 10^{-6} * F_R \quad (8c)$$

$$S_f(t) = k_d V_z C_f(t) * 1.0 * 10^{-6} * F_R m \quad (8d)$$

$$G_f(t) = \frac{m_p R_g T}{P} \quad (9)$$

where P is the atmeric pressure, taken as 97.665 kPa [35].

2.3.5 Thermal comfort model

The thermal comfort model was developed to determine the indoor air temperature setpoint under different ventilation modes. In this study, the adaptive comfort model was adopted. Although ASHRAE Standard 55 [36] proposes that the adaptive comfort model is only applicable to naturally ventilated buildings, several studies have pointed out that it is also applicable to hybrid ventilated buildings [14]. The operative temperature based on the adaptive thermal comfort model can be calculated as:

$$T_{OP,setpoint} = 0.31 * T_o + 17.8 \qquad (\text{if } 10℃ \le T_o \le 33.5℃) \qquad (10a)$$

Figure 5 presents the variation of the operative temperature setpoint using the adaptive thermal comfort model. It can be observed that the temperature setpoint in Guangzhou was the highest, followed by Shanghai, Beijing, Kunming and Harbin.

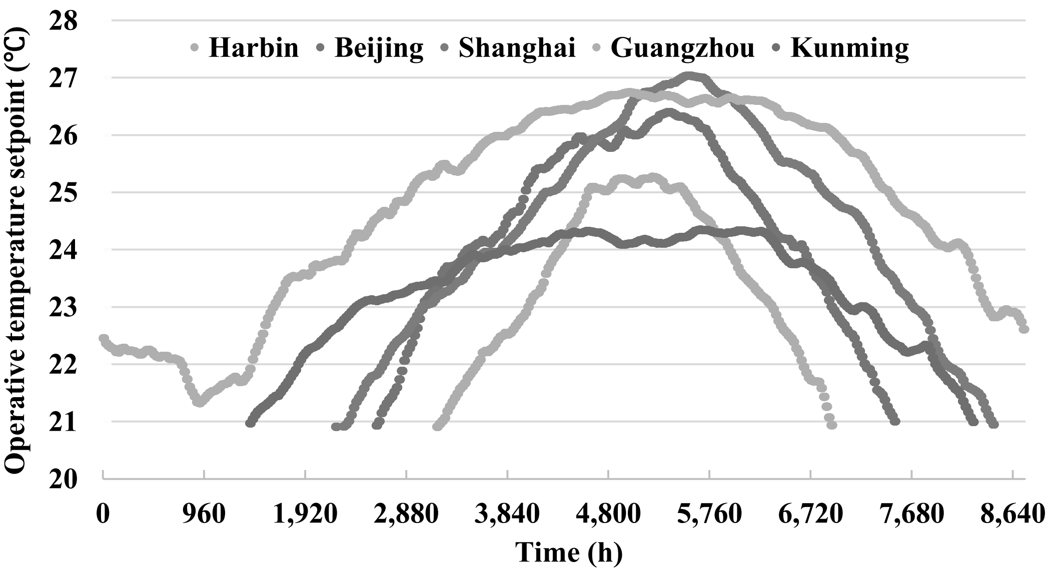

Figure 5. Variation of temperature setpoint using adaptive thermal comfort model

Two thermal comfort ranges were defined by ASHRAE Standard 55 [36], which were 80% acceptability (T_{OP}±3.5℃) and 90% acceptability (T_{OP}±2.5℃). The 80% acceptability temperature range was adopted in this study.

The T_o is outside the range of 10℃~33.5℃, the operative temperature can be calculated as the weighted average of the indoor drybulb temperature and mean radiant temperature. For occupants engaged in nearly sedentary physical activity (metabolic rate between 1.0 and 1.3), not exposed to direct sunlight and indoor air velocity less than 0.2 m/s, T_{OP} can be approximated as [36].

$$T_{OP,setpoint} = (T_{MRT} + T_{in})/2 \quad (10b)$$

Based on the adaptive thermal comfort model, a new cooling indoor temperature setpoint can be obtained, which could be higher than the traditional cooling temperature setpoint, thus reducing the energy consumption of the HVAC system [36]:

$$T_{cooling,newsetpoint} = 2T_{OP,setpoint} - T_{MRT} \quad (11)$$

2.3.6 Ventilation control strategies

Ventilation control strategies were developed to determine how to use the outside air for free cooling under different ventilation modes. Three types of ventilation for windows opening were studied: (1) mechanical ventilation (MV); (2) hybrid ventilation (HV1) that considers the outdoor air temperature only; (3) hybrid ventilation (HV2) that considers both the outdoor air temperature and $PM_{2.5}$ concentration. The control strategies for the three ventilation modes are described as below:

(1) Under MV mode, cooling is solely provided by the air conditioning system, and the minimum fresh air flow rate is provided by the mechanical system.

(2) Under HV1 mode, if the zone air temperature is higher than the outside air temperature and higher than 22℃, dewpoint temperature is lower than 24ºC (concluded from [42]), and the outside air temperature is lower than the upper limit of the adaptive thermal comfort model (with 80% acceptability), the air-conditioning system is close, and the natural ventilation system provides cooling and fresh air; if the operative temperature is outside the acceptable range, the air conditioning system is turned ON and the natural ventilation is turned OFF, and mechanical system provides the minimum fresh air flow rate.

(3) Under HV2 mode, if the zone air temperature is higher than the outside air temperature and higher than 22℃, dewpoint temperature is lower than 24℃, and the outside air temperature is lower than the upper limit of the adaptive thermal comfort model (with 80% acceptability), and outside $PM_{2.5}$ concentration is ≤35 μg/m^3, the air-conditioning system is close, and the natural ventilation system provides cooling and fresh air; Otherwise the air conditioning

system is turned ON and the natural ventilation is turned OFF, and mechanical system provides the minimum fresh air flow rate.

For mechanical ventilation, free cooling can also be provided by turning ON the economizer. For the VRF system, the fresh air flow rate is fixed and there is no air economizer, which is the case in China. For the VAV and CAV systems, air economizer can be ON to maintain the mixed air temperature at its setpoint, when the outside air enthalpy is lower than the return air enthalpy.

2.4 Evaluation indices

The indices were developed to evaluate the energy saving potential of natural ventilation. The proportion of natural ventilation hours (R_{hour}), energy saving by natural ventilation (NV_{energy}), and utility costs saving by natural ventilation (NV_{cost}), were adopted and can be calculated by equations (12-14):

$$R_{hour} = \frac{N_{NV}}{N_{OCC}} \tag{12}$$

$$NV_{energy} = \frac{Energy_{MV} - Energy_{NV}}{A_{floor}} \tag{13}$$

$$NV_{cost,NV1} = \frac{Cost_{NV} - Cost_{MV}}{Cost_{MV}} \tag{14}$$

3. Results and Discussion

3.1 Results of pollution transportation model validation

The simulation results of the indoor $PM_{2.5}$ concentration were compared with the experimental results from an office room with a total floor area of 25.6 m^2 and a window area of 5.5. m^2, located in Wuhan, China. The office has not been renovated during the past five years, and is a non-smoking office. The experiment was carried out from May 12, 2018 to May 14, 2018 with a total duration of 72 hours and 5 minutes time interval. The hourly average indoor and outdoor $PM_{2.5}$ concentrations, window opening status (0 refers to fully close and 1 refers to fully open), are presented in Figure 6. The indoor $PM_{2.5}$ generation mostly came from occupants' activities with a generation rate of 6.952×10^{-9} m^3/s. Figure 7 presents the measured wind speed, wind direction and the number of occupants during the experiment.

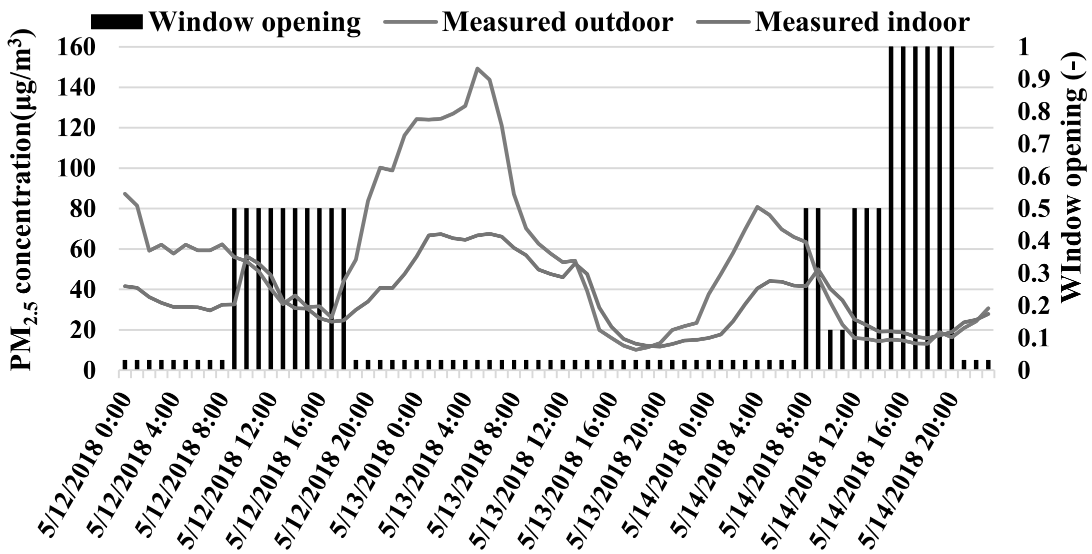

Figure 6. Measured indoor and outdoor $PM_{2.5}$ concentrations and window opening level

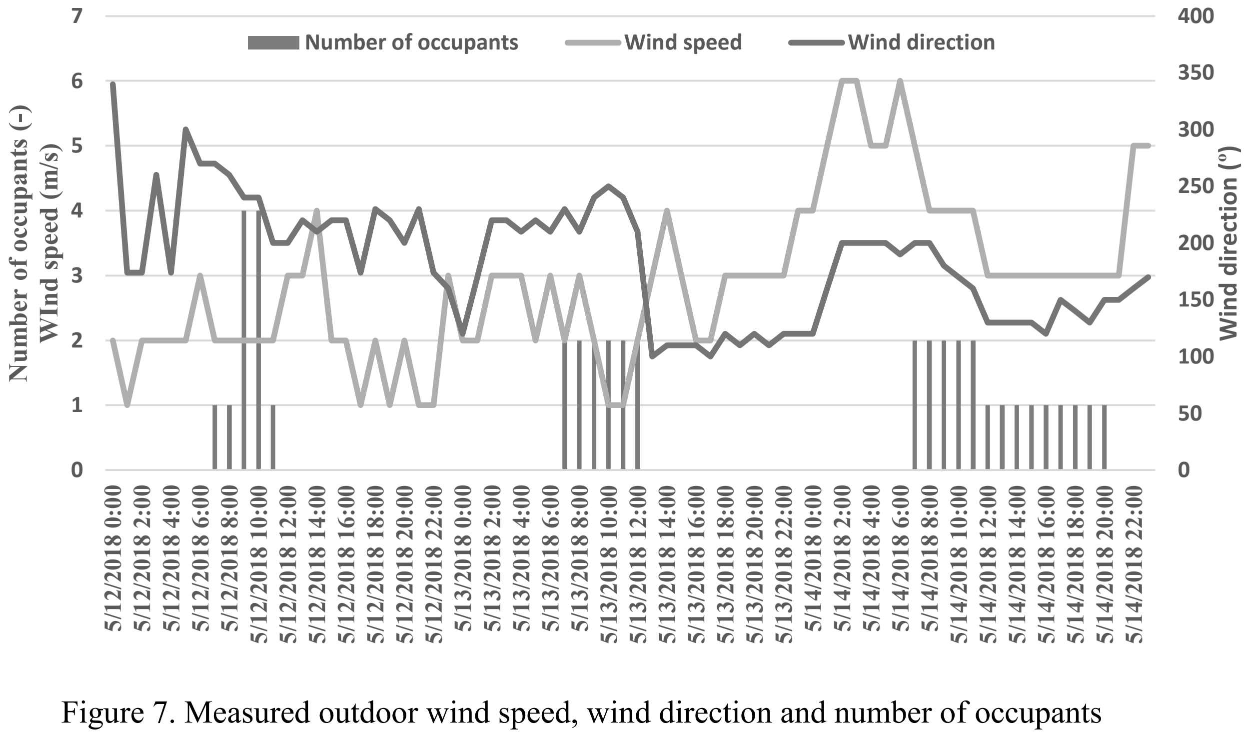

Figure 7. Measured outdoor wind speed, wind direction and number of occupants

The comparison between the results of simulation and experiment is presented in Figure 8. The mean average absolute and relative errors were 3.32 μg/m^3 and 1.93%, respectively. The correlation coefficient between the simulated and the measured values was 0.95, indicating good agreements between the two sets of results.

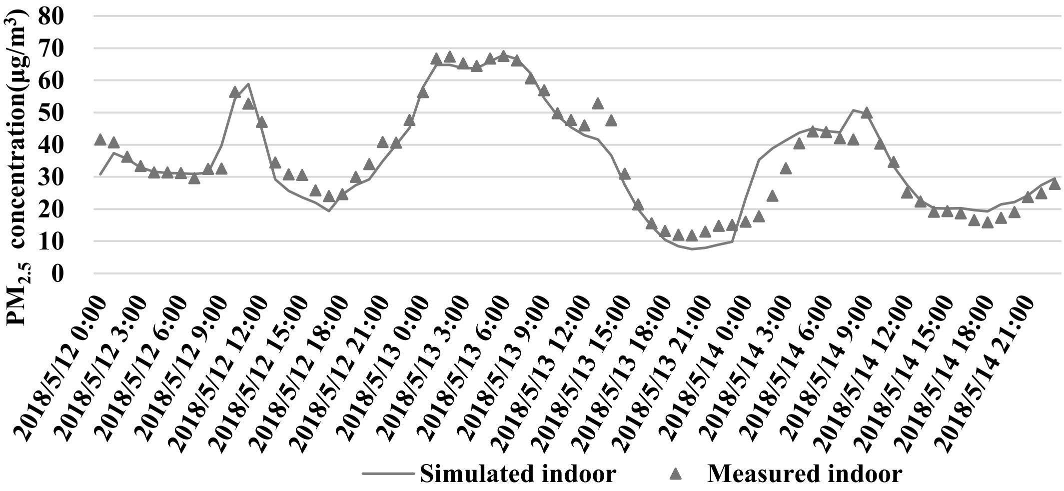

Figure 8. Indoor $PM_{2.5}$ concentration, measured vs. simulated.

3.2 Results of NV energy saving potential using typical year meteorology data

3.2.1 NV hours

Figure 9 presents the NV hours and average proportion of NV hours for different cities and air-conditioning systems. The NV hours for different HVAC systems varied slightly due to differences in indoor operative temperature during operation. Due to its mild weather condition, the NV hours of Kunming (mild region) was the highest among all the cities, exceeding 2100 hours when outdoor air pollution was not taken into account, followed by Guangzhou (hot summer and warm winter region), Shanghai(hot summer and cold winter region), Harbin (severe cold region) and Beijing (cold region). The average proportion of NV hours were in the range of 28%~67% under HV1 mode and 15%~55% under HV2 mode, respectively. The reduction on the NV hours due to air pollution for Kunming, Guangzhou, Shanghai, Beijing, and Harbin were 12%, 23%, 16%, 16% and 2%, respectively. The impact of air pollution on the NV hours of Guangzhou was the highest. This is because a high outdoor $PM_{2.5}$ concentration can be observed in winter and natural ventilation can be used in winter in Guangzhou which has a hot summer and warm winter climate. For Harbin, natural ventilation is not available in winter as the outdoor air temperature is too low, and therefore the impact of the air pollution on the NV hours is not obvious.

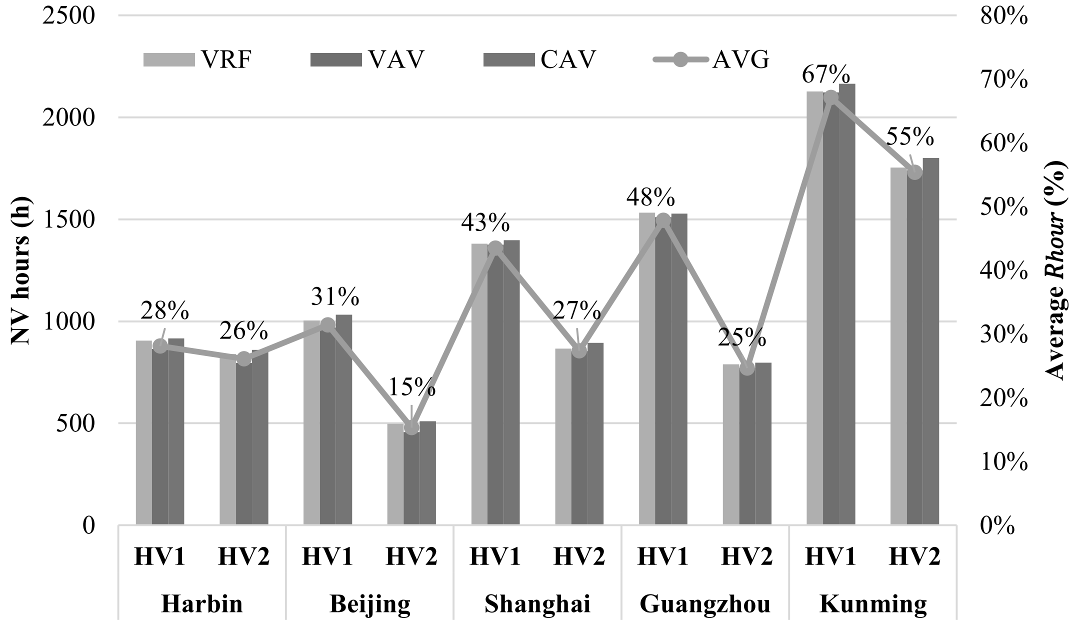

Figure 9. NV hours for different cities

3.2.2 Energy saving by natural ventilation

Figure 10 presents the annual building energy consumption (ABEC) under different ventilation modes. The gas consumption was converted into kWh using the conversion coefficient of 0.2778 MJ/kWh [26]. It can be observed that the ABEC was in the range of 68.14~123.65 kWh/m^2. The ABEC in Harbin was the highest and in Kunming was the lowest. The energy consumption, from the lowest to the highest, were the ones under HV1 mode, HV2 mode and MV mode, respectively. In terms of air-conditioning system, the CAV system had the highest energy consumption, followed by the VAV system and the VRF system. The simulation outcomes are consistent with the statistical analysis results from Li et al. [37].

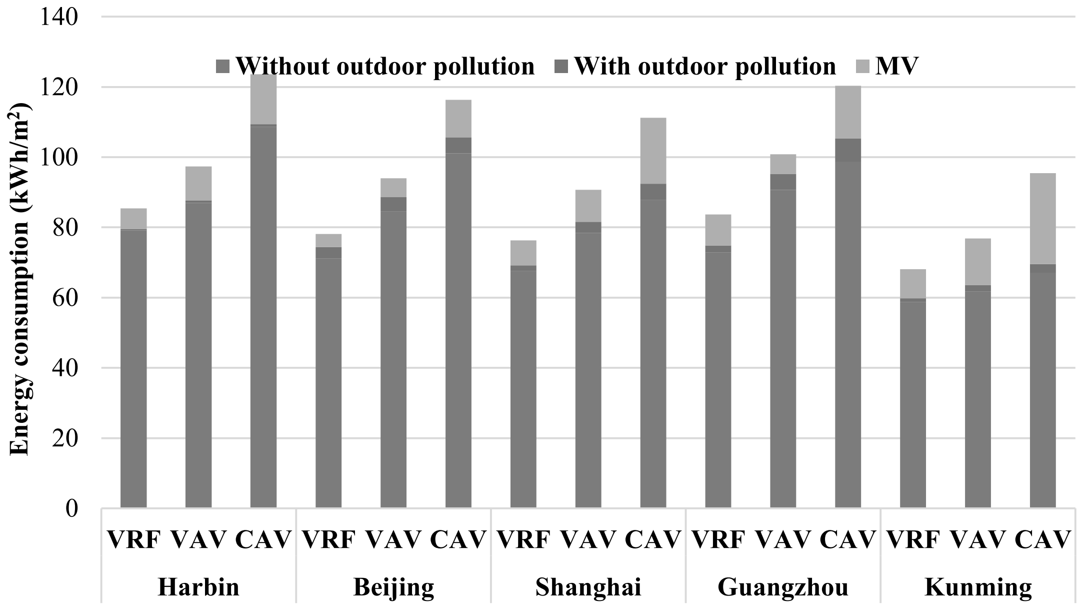

Figure 10. Annual building energy consumption for different cities

Figure 11 presents the energy savings by natural ventilation. The energy savings under HV1 and HV2 modes were in the range of 6.24~28.32 kWh/m^2 and 3.71~25.91 kWh/m^2, respectively. The CAV system had the highest energy saving potential, followed by the VAV systems, and VRF system in four cities. In Guangzhou, the savings of VRF were higher than those of VAV, probably because the savings from air economizer was high which results in low natural ventilation energy savings. VRF systems provide only a minimum fresh air flow rate to the space and thus natural ventilation can effectively save the cooling energy, however, the proportion of cooling energy of the VRF system is smaller than that of other systems, leading to the lowest energy savings in the other four cities. The economizer of the all air system (CAV and VAV systems) can provide free cooling, which has a negative impact on NV energy savings. However, due to the large proportion of the fan energy consumption, especially the CAV system, the NV energy saving is still high. The energy savings in Beijing was the lowest under NV2 mode due to high outdoor $PM_{2.5}$ concentration. The energy savings in Harbin was the lowest under NV1 mode due to low natural ventilation hours. The energy savings was the highest in Kunming due to the mild weather condition and low outdoor $PM_{2.5}$ concentration. In terms of average energy savings, under HV1, the amount of savings in Kunming, Guangzhou, Harbin and Shanghai, were 1.68, 1.35, 1.0, and 1.41 times that in Beijing, respectively. Under HV2 modes, the amount of savings in Kunming, Guangzhou, Harbin and Shanghai, were 2.41, 1.49, 1.5 and 1.78 times that in Beijing, respectively.

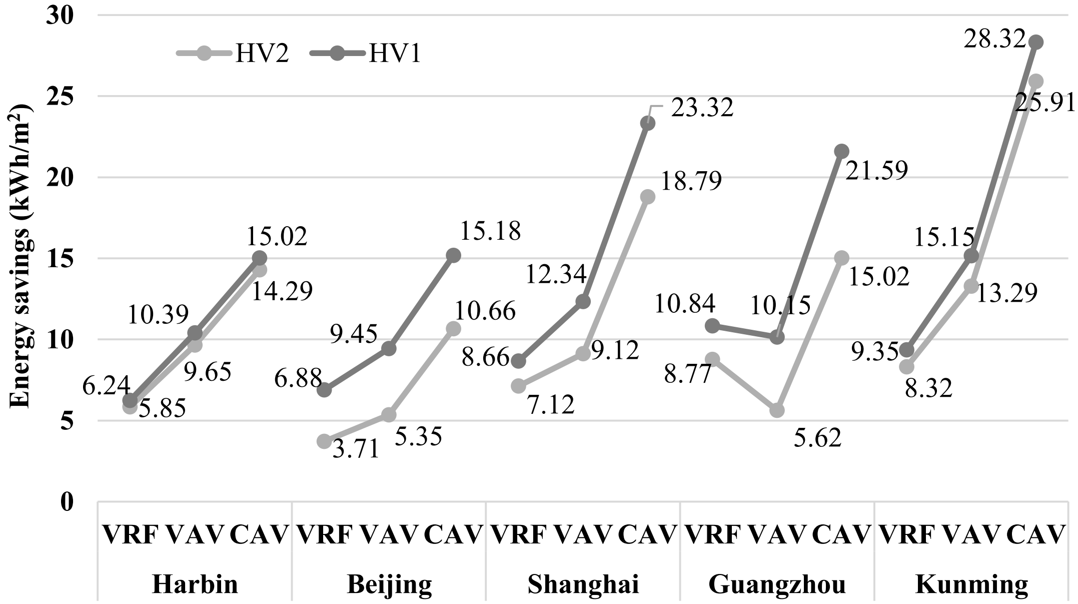

Figure 11. Energy savings by natural ventilation

3.2.3 Cost saving by natural ventilation

Figure 12 presents the utility cost in different cities under different ventilation modes. The electricity price was taken as 0.611¥/kWh [38], and gas price was 0.0778¥/MJ [39]. According to Figure 9, the utility cost in Guangzhou was the highest, which was 53,135¥/year (73¥/m^2 per year). The utility cost in Kunming was the lowest, which was 80% of that in Guangzhou. The annual cost savings of natural ventilation was 3.57~16.85 ¥/m^2. When outdoor $PM_{2.5}$ pollution is taken into account, the cost saving was reduced by 5.0%~47%. The cost savings of CAV system and VAV system were 1~3 times that of the VRF system.

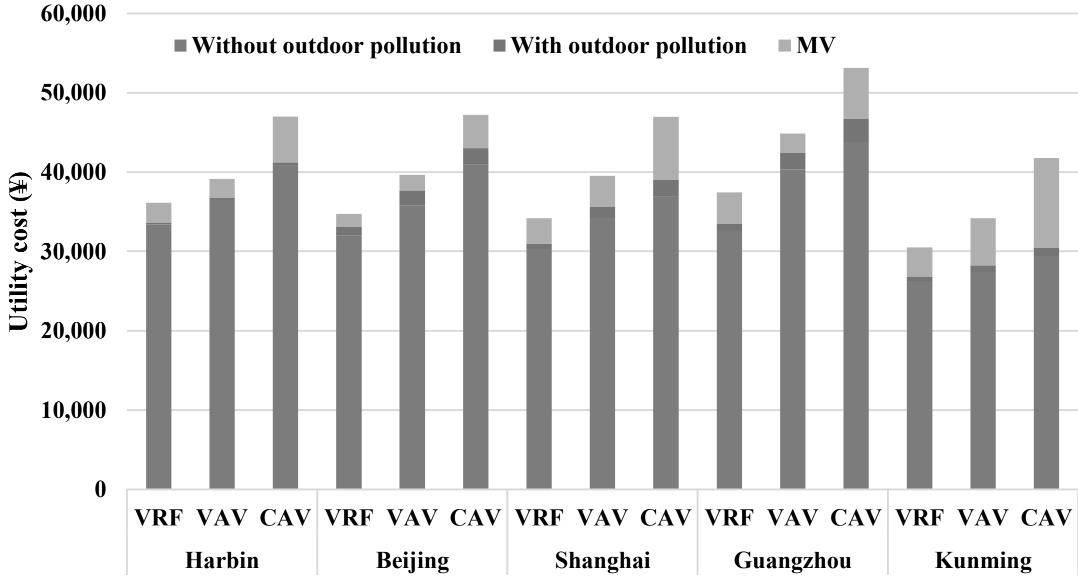

Figure 12. Utility cost in different cities

3.3 Results of energy savings under actual climate condition

As the actual pollution varies every year and the outside air humidity, solar radiation intensity and wind profile are different from the typical year meteorology data. The annual energy savings by natural ventilation under actual climate conditions were calculated and listed in Table 5. The average values are compared with the ones using the TMY data using different approaches. Overall, the energy savings predicted using the typical meteorology data from 2016 to 2020 approach is comparable to the average energy savings from 2016 to 2020 as predicted by the actual yearly meteorology data with a difference in the range of -7%~7%. The CSWD TMY data approach tends to overestimate the natural ventilation energy saving due to global warming effect that causes the outdoor air temperature to increase in recent years.

Table 5 Energy savings by natural ventilation

City	Ventilation mode	2016 (kWh/m^2)	2017 (kWh/m^2)	2018 (kWh/m^2)	2019 (kWh/m^2)	2020 (kWh/m^2)	Average (kWh/m^2)	TMY (2016~2020 OAT)		TMY (2016~2020 $PM_{2.5}$ Pollution)		TMY (CSWD)	
								NV_{energy} (kWh/m^2)	Diff. (-)	NV_{energy} (kWh/m^2)	Diff. (-)	NV_{energy} (kWh/m^2)	Diff. (-)
Harbin	HV1	9.03	9.36	11.22	11.10	10.96	10.33	10.39	1%	9.39	-9%	11.39	10%
	HV2	7.89	8.33	10.64	10.40	10.64	9.58	9.65	1%	8.59	-10%	10.50	10%
Beijing	HV1	9.34	8.49	8.75	7.89	9.86	8.87	9.45	7%	8.21	-7%	11.85	34%
	HV2	4.94	5.34	5.88	5.12	6.01	5.46	5.35	-2%	5.80	6%	7.00	28%
Shanghai	HV1	14.29	12.99	10.68	13.86	13.13	12.99	12.34	-5%	13.50	4%	13.70	5%
	HV2	10.20	10.13	8.10	9.75	10.31	9.70	9.12	-6%	9.74	0%	10.05	4%
Guangzhou	HV1	10.53	9.35	10.04	9.92	9.80	9.93	10.15	2%	9.86	-1%	12.66	28%
	HV2	6.00	4.58	5.90	5.70	7.90	6.01	5.62	-7%	4.82	-20%	8.31	38%
Kunming	HV1	15.33	15.45	15.79	14.75	15.05	15.27	15.15	-1%	14.50	-5%	15.33	0%
	HV2	13.39	13.41	12.90	13.09	13.32	13.22	13.3	1%	12.88	-3%	13.80	4%

3.4 Resuls of indoor $PM_{2.5}$ concentration

The variations of the indoor $PM_{2.5}$ concentration during working days of the building using VAV system, the most widely used system in China, are presented in Figure 13. It can be found that 90% of the time the indoor $PM_{2.5}$ concentration fell within the range of 6.1~67.6 μg/m^3, which was consistent with the measurement results. In Beijing and Harbin, the indoor $PM_{2.5}$ concentration exceeded the 50 μg/m^{3}limit required by the indoor air quality standard [40] for over 10 days. The high concentrations occurred during the heating season and coincided with high outdoor $PM_{2.5}$ concentrations as minimum fresh air flow was required during the occupied hours. In this case, it is necessary to have an indoor air purification device.

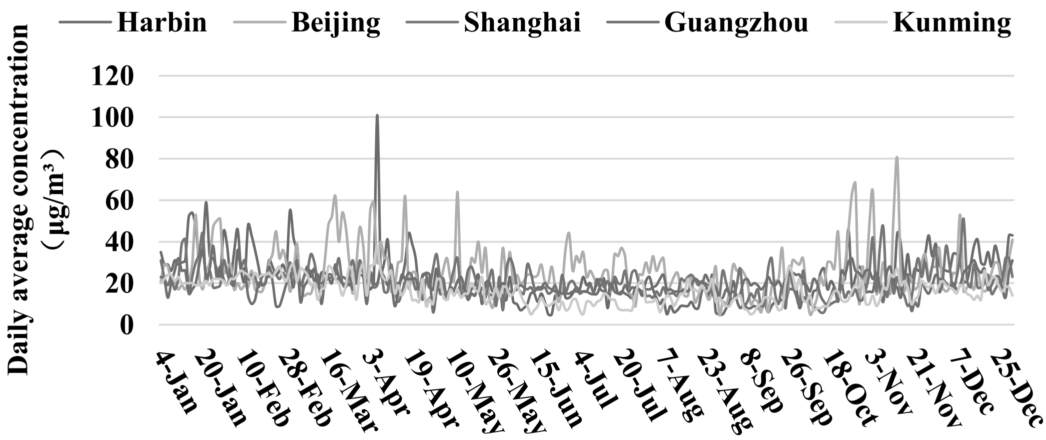

Figure 13 Daily average working day indoor $PM_{2.5}$ concentration

3.5 Discussion

In this study, the indoor operative temperature and outdoor $PM_{2.5}$ concentration were used to determine the suitability of natural ventilation. When the outdoor pollution was not taken into account, the NV hours were in the range of 28%~67% and when it was taken into account, they were reduced to 15%~55%. In addition, Kunming was found to have the greatest NV energy saving potential. The findings were consistent with the results from Tong et al. [6] and Li et al. [16]. Although Xu et al. [41] proposed to use indoor instead of outdoor $PM_{2.5}$ concentration to determine the suitability of natural ventilation, this study found that for non-smoking office space, using outdoor $PM_{2.5}$ concentration as an indicator for natural ventilation already can ensure the indoor air quality during cooling season. Moreover, it is easier to be applied in office buildings.

In this study, the minimum fresh air was ensured while maximizing the utilization of natural ventilation. In addition, the operative temperature was used to ensure the indoor thermal comfort condition, which differs from other studies using a fixed range for indoor air temperature [15] or a fixed temperature setpoint [14]. Furthermore, it is proposed to limit the natural ventilation when unoccupied, which considers occupants' habit of closing doors and windows when leaving the building. It is very effective when it rains or the outdoor air quality is poor at night, although in this case the energy-saving by night time ventilation is not considered.

4. Conclusion

In this paper, the energy saving potential of natural ventilation in five representative cities across different climate regions in China was investigated. The research effectively addressed the research gaps through the development of a computer model which includes a smart window control system that adjusts the window opening area based on the temperature difference between indoor and outdoor environments, an adaptive thermal comfort model that resets the space temperature setpoint according to the indoor operative temperature, a pollution transportation model for calculating indoor $PM_{2.5}$ concentration levels. The computer model was employed to evaluate the energy-saving potential of natural ventilation in three air-conditioning systems while maintaining a minimum fresh air rate during the occupied natural ventilation period. The assessment was conducted using three evaluation indices to comprehensively analyze the outcomes. The following conclusions can be made:

1) The average proportion of natural ventilation hours were in the range of 28%~67% without considering the outdoor $PM_{2.5}$ concentration and 15%~55% when the outdoor $PM_{2.5}$ concentration was taken into account. The reduction on the natural ventilation hours is due to air pollution for Kunming, Guangzhou, Shanghai, Beijing, and Harbin are 12%, 23%,16%, 16% and 2%, respectively; Kunming had the highest number of natural ventilation hours, followed by Guangzhou (hot summer and warm winter region), Shanghai (hot summer and cold winter region), Beijing (cold region), and Harbin (severe cold region). The natural ventilation hours differ slightly with different types of air-conditioning systems due to differences in actual operation performance.
2) The energy savings without/with considering the outdoor $PM_{2.5}$ concentration were in the range of 6.24~28.32 kWh/m^2 and 3.71~25.91 kWh/m^2, respectively; The CAV systems had the highest energy saving potential, followed by VAV system and VRF system.
3) The annual cost savings of natural ventilation was 3.57~16.85 ¥/m^2 when outdoor $PM_{2.5}$ pollution was not considered. When outdoor $PM_{2.5}$ pollution was taken into account, the cost saving would be reduced by 5.0%~47%. The cost savings of CAV system and VAV system were 1~3 times that of the VRF system.
4) During the working days, most of the time the daily average indoor $PM_{2.5}$ concentration was below the limit of 50 μg/m^3 as set by the indoor air quality standard, which means that good indoor air quality can be maintained for non-smoking offices when the minimum fresh air flow rate is ensured.

The originality of this study lies in the evaluation methodology, comprehensive approach, sophisticated computer model, comparative analysis of air-conditioning systems, and practical implications for energy-savings. The research outcomes can assist building facility engineers in persuading building owners to adopt ventilation control strategies for different building mechanical systems, aiming to achieve energy savings while ensuring indoor thermal comfort. Additionally, smart window controllers are also recommended to be installed to facilitate effective implementation of the ventilation control strategies.

Future research directions should encompass the exploration of more HVAC systems, such as fan coil units, and include a wider range of building types, such as shopping malls and libraries. Furthermore, it is important to conduct field verification to assess the practical application of ventilation control strategies in relevant buildings.

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