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Measurement and simulation of indoor air quality and energy consumption in two Shanghai office buildings with variable air volume systems☆

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Abstract

Two modern office buildings in Shanghai with typical variable air volume (VAV) systems were selected for research. Four separate spaces on a standard office floor in each building facing different directions (north, south, east, and west) were selected for thorough site measurements of outdoor airflow rates and indoor air quality (concentrations of CO_2 and PM_{10}) during typical days of the four seasons (summer, autumn, winter, spring). Computer simulations and calculations were also done of outdoor airflow rates and CO_2 concentrations in the four-test spaces on an hourly basis for the entire year. In addition to the site measurements, monthly electrical consumption for the two buildings was recorded or estimated. Simulations and calculations were performed of the buildings' energy consumption and energy cost using two different outdoor air control strategies of a typical VAV system as well as a fan coil unit (FCU) system. The site-recorded data, or estimated data, and simulation results are compared and analyzed. The study reveals that in a VAV system, the outdoor airflow rate distributed to each zone varies greatly, especially during part-load hours, making it difficult to always ensure sufficient outdoor air in each zone and avoid indoor air quality (IAQ) problems. However, this problem can be prevented by using appropriate outdoor air control strategies—e.g. a fixed high level total outdoor airflow rate.

Keywords: VAV system; Fan powered box (FPB); IAQ; Energy consumption

1. Introduction

In Shanghai, many high-rise buildings have been built during the last 20 years. VAV systems have become popular with design engineers because of the improved energy efficiency and greater flexibility than constant air volume (CAV) systems and fan coil unit (FCU) systems, especially when used in office buildings. However, occupants' comfort may be sacrificed when energy is saved. As the name (VAV) implies, VAV systems vary the volume of air delivered by HVAC systems. In order to maintain thermally comfortable conditions within different zones of a building, this approach varies the volume of air delivered to each zone, while the temperature to most locations remains constant. If series-fan-powered-mixing-boxes are used as terminals, the volume of the primary air (delivered by primary air handling unit to FPBs; refer to Fig. 1) varies while the volume of total air remains constant in each zone. The maximum total airflow of a VAV system is designed to maintain thermally comfortable conditions for even the most extreme winter and summer design conditions. During the part-load conditions when the thermal loads are reduced, a basic VAV system may cause a decrease in the total airflow rate [4], and a VAV–FPB system may cause a decrease in the total primary airflow rate. If the outdoor air control approach merely relies on the quantity of outdoor air introduced as being a constant percentage of the total supply air (or total primary air), then, when supply volume is reduced, the outdoor airflow rate can fall below American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) minimum recommended values [2]. An alternative control approach can be used to ensure a constant flow of total outdoor ventilation air. However, ensuring the proper flow rate of total outdoor ventilation air across the building envelope does not ensure zone-level delivery of outdoor ventilation air to every occu-

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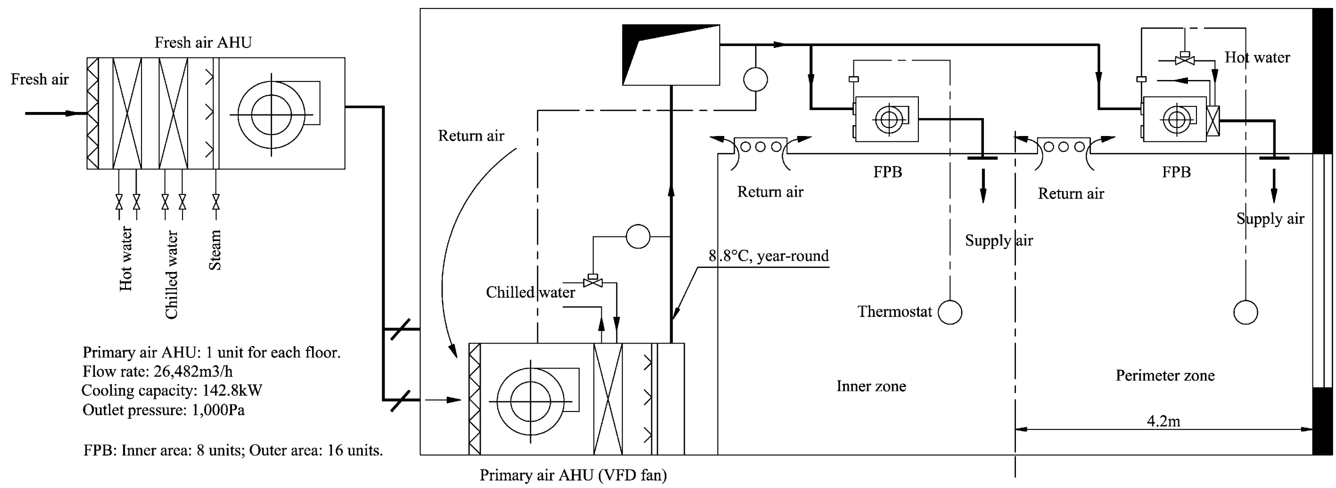


Fig. 1. Scheme of VAV system on a standard office floor in Building A.

pant of the building. The outdoor airflow rate delivered to each zone varies when the load changes, causing the uneven distribution of outdoor air in certain zones, some of which may fall below ASHRAE minimum recommended ventilation values [2].

Many researchers have discussed the energy advantages and outdoor air shortcomings and proper ventilation control strategies for VAV systems [4–12]. For example, an EPA-sponsored study [5] compared the total outdoor airflow rates of CAV systems and VAV systems in large office buildings under different outdoor air control and economizer strategies. Also, Ke et al. [7] simulated eight different outdoor air control strategies and reported that without tempering at the terminal boxes, no outdoor air strategy could meet the outdoor air requirements under part-load conditions; of the eight strategies, the fixed outdoor air percentage strategy produced the worst results. Similarly, Shelquist [8] demonstrated that it was possible for a VAV system to meet ventilation requirements without reducing energy efficiency as long as proper outdoor air control strategies were used. Finally, Feilker [10] studied the most common outdoor air control methods of VAV systems and addressed the importance of balancing and commissioning.

In order to evaluate the compatibility and trade-off between indoor air quality and energy efficiency of the VAV systems in real buildings, both site measurements and dynamic simulations were done on outdoor air distribution, indoor air quality and energy consumption in the two Shanghai high-rise office buildings with VAV systems.

2. Building description

Two high-rise commercial buildings located in the Lujiazui Finance & Trade Zone in the Pudong New Area in Shanghai, called Building A and Building B in this paper, were selected for measurement and research. Table 1 lists relevant information about the two buildings and their HVAC systems. Both buildings used series-fan-powered-mixing-boxes as terminals. An air velocity sensor and a motor-driven damper were installed at the inlet of each FPB to control the primary air volume via the direct digital control (DDC) and the room thermostat. The fans in the FPBs ran continuously at a constant speed to mix primary air and indoor air, and then supplied the mixed air to the rooms through a duct.

Fig. 1 shows the scheme of a VAV system on a standard office floor in Building A. The VAV system in Building B was the same except that the primary air temperature and the capacity of the fresh air unit (FAU) were different. The primary air temperature of the VAV system in Building A (8 °C) was somewhat lower than that of Building B (16 °C). The air handling and distribution process of the VAV systems in the two buildings was as follows:

- the FAU (placed in one or more central HVAC plant rooms) handled the outdoor air;
- the primary air unit (PAU, one on each floor) handled a mixture of the outdoor air from the FAU and the primary return air into the primary air;
- the primary air was again mixed with the secondary return air in the FPB;the mixed air was delivered into the room.

3. Site measurements

Site measurements were done on typical days of each season. The summer and autumn tests were performed in 2000 and the winter and spring tests were performed in 2001. In each building, four separate rooms facing different directions on a standard office floor (the 8th floor in Building A; the 9th floor in Building B) and served by the VAV system were selected as test spaces. Table 2 lists the test dates, space areas and occupant densities. As shown in Table 2, the actual occupancies of the test spaces were below the design occupancies (shown in Table 1) as well as the 7 person/

Table 1
Building description

	Building A	Building B
Total area (m^2)	300000	75000
Height (m)	420.5	140
Number of floors	Under-ground floors: 3; above-ground floors: 88	Under-ground floors: 3; above-ground floors: 37
Function	Office and hotel	Office
Primary energy system	Cooling: six units 4220 kW and two units 1406 kW centrifugal electric chillers (total: 28136 kW); heating: four units 10 t/h oil/gas steam boilers	Cooling: five units 1934 kW centrifugal electric chillers (total: 9672 kW); heating: two units 2600 kW oil/gas hot water boilers; two units 0.86 t/h oil/gas steam boilers
HVAC system type	Office (3rd–50th floor): VAV–FPB system; hotel (53rd–87th floor): four-pipe FCU system	1st–27th floor: VAV–FPB system; 28th–37th floor: four-pipe FCU system
Standard office floor		
Floor area (m^2)	2500	1000
Floor-to-floor height (m)	4	3.7
Design occupancy (m^2 per person)	9.2 (10.9 person/100 m^2)	8 (12.5 person/100 m^2)
Primary air AHU	Design primary airflow rate: 26482 m^3/h; cooling capacity: 142.8 kW; primary air temperature: 8.8 °C (year-round)	Design primary airflow rate: 30000 m^3/h; primary air temperature: 16 °C (year-round)
Number of FPB	24 (16 in perimeter zones with hot water re-heater; 8 in internal zone)	20 (12 in perimeter zones with hot water re-heater; 8 in internal zone)
Depth of perimeter zone (m)	4.2	3

100 m^2 limit recommended by ASHRAE Standard 62-1989 [2] for office buildings.

3.1. Outdoor airflow rate

An indirect method was used to measure outdoor airflow rate. In the two buildings, the primary airflow rate of each FPB (Q_{PA}) was recorded by building automation (BA) systems on an hourly basis. Every 5 min, the temperatures of outdoor air (T_{OA}), primary return air (T_{RA}), and their mixture (T_{MA}) before the cooling coil and the heating coil in PAU were measured with self-recording thermometers. The ratio of outdoor air to primary air (R_{OA}) was then calculated based on the three temperatures (T_{OA}, T_{RA}, T_{MA}). This mixed air temperature comparison method was adapted from the mixed air enthalpy comparison method by disregarding the changes in the humidity ratio and specific heat of the air [11]. The mixed air temperature comparison method was not recommended by Feilker [10] and Schroeder et al. [11] because of its lack of accuracy. Temperatures are generally easy to measure with standard instrumentation, but this is not true of the mixed air temperature (T_{MA}). Since the temperature of mixed air must be measured before it passes through any coils or fans, stratification of the air can make accurate temperature readings difficult to obtain. Moreover, large errors in calculating outdoor airflow rate can occur when the difference between T_{OA} and T_{RA} becomes small. Nonetheless, this method was used for the outdoor airflow rate measurement in the two buildings because it was very difficult to find a proper position to do direct airflow measurement and it was not possible to use tracer gas in the occupied buildings.

Table 2
Site test dates, test space areas and occupant densities of two buildings

			Building A			Building B		
Site test date	Summer		July 19, 2000			July 12, 2000		
	Autumn		November 21, 2000			November 16, 2000		
	Winter		February 16, 2001			February 14, 2001		
	Spring		April 26, 2001			April 12, 2001		
	Room no.	Facing	Floor area (m^2)	Occupant number	Occupancy (person/100 m^2)	Floor area (m^2)	Occupant number	Occupancy (person/100 m^2)
Test space	1	South	17.5	1	5.7	238	10	4.2
	2	East	133	5	3.8	73	4	5.5
	3	North	54	1	1.9	87	1	1.1
	4	West	94	5	5.3	44	2	4.5

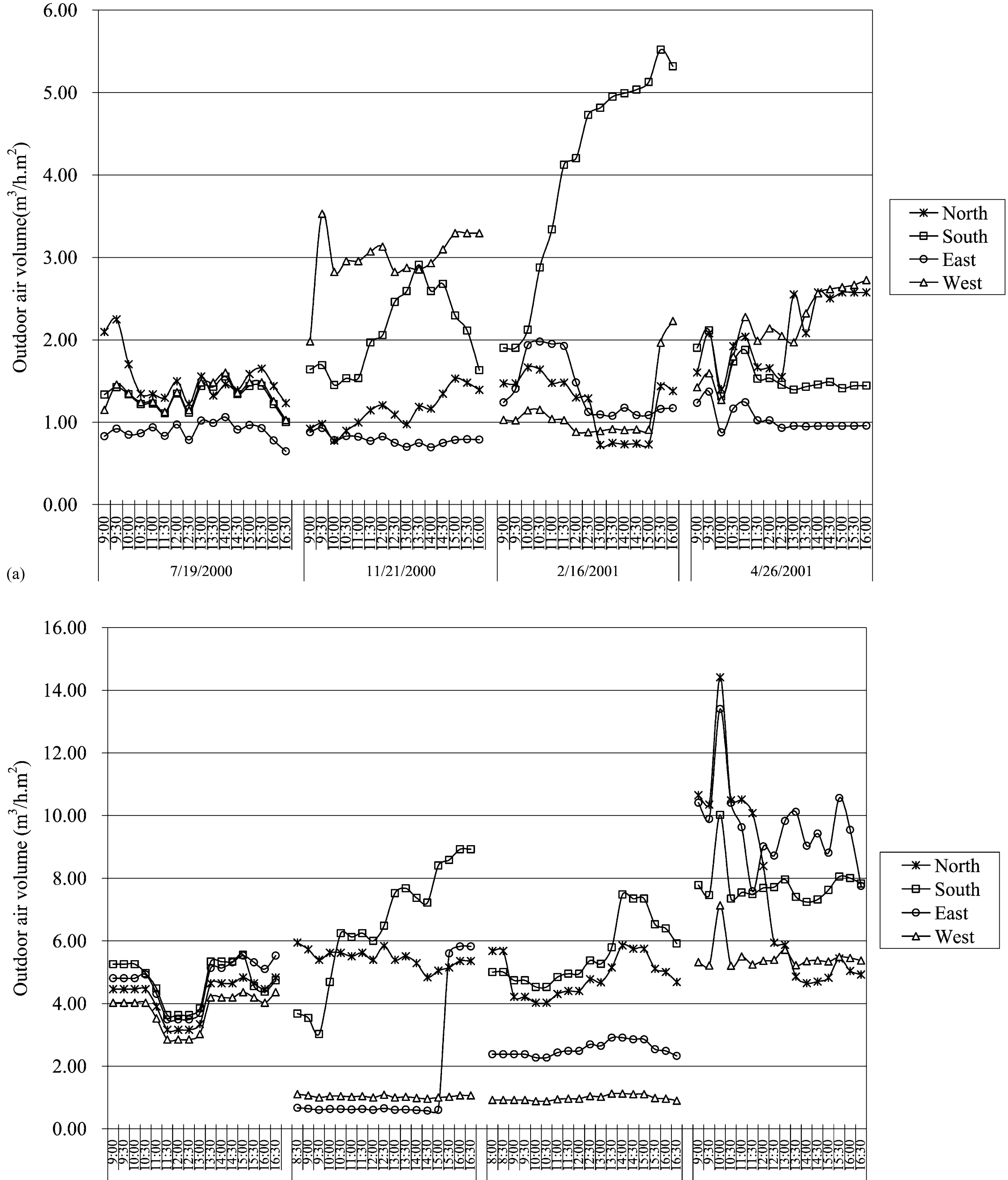


Fig. 2. (a) Outdoor airflow rate distributed to four-test spaces averaged for floor area in Building A (measured). (b) Outdoor airflow rate distributed to four-test spaces averaged for floor area in Building B (measured).

Knowing R_{OA}, the outdoor airflow rate delivered by each FPB into a space could be calculated with the following equation:

$$Q_{OA(i)} = Q_{PA(i)} R_{OA} \tag{1}$$

where $Q_{OA(i)}$ is the outdoor airflow rate delivered by i FPB into space, $Q_{PA(i)}$ the primary airflow rate of i FPB, and R_{OA} is the ratio of outdoor air to primary air.

If one space was served by more than one FPB, outdoor airflow rates of all the FPBs were added and then averaged for space area and occupant number, respectively. (See Figs. 2(a)–3(b); space areas and occupant numbers refer to Table 2.) In Fig. 2(a) and (b), the differences in outdoor airflow rate for each m^2 of floor area in different spaces were less in the summer (July 19, 2000 for Building A and July 12, 2000 for Building B) than in the other seasons, indicating that the outdoor air distribution in these spaces was more even in the summer. Also, the changing ranges of outdoor airflow rates were smaller in the summer than in the other seasons. As July 19, 2000 and July 12, 2000 are two typical summer days in Shanghai, the VAV systems can be regarded as operating under full-load conditions on those 2 days. In Building A and Building B, the standard office floor is divided into internal zones and perimeter zones, because the

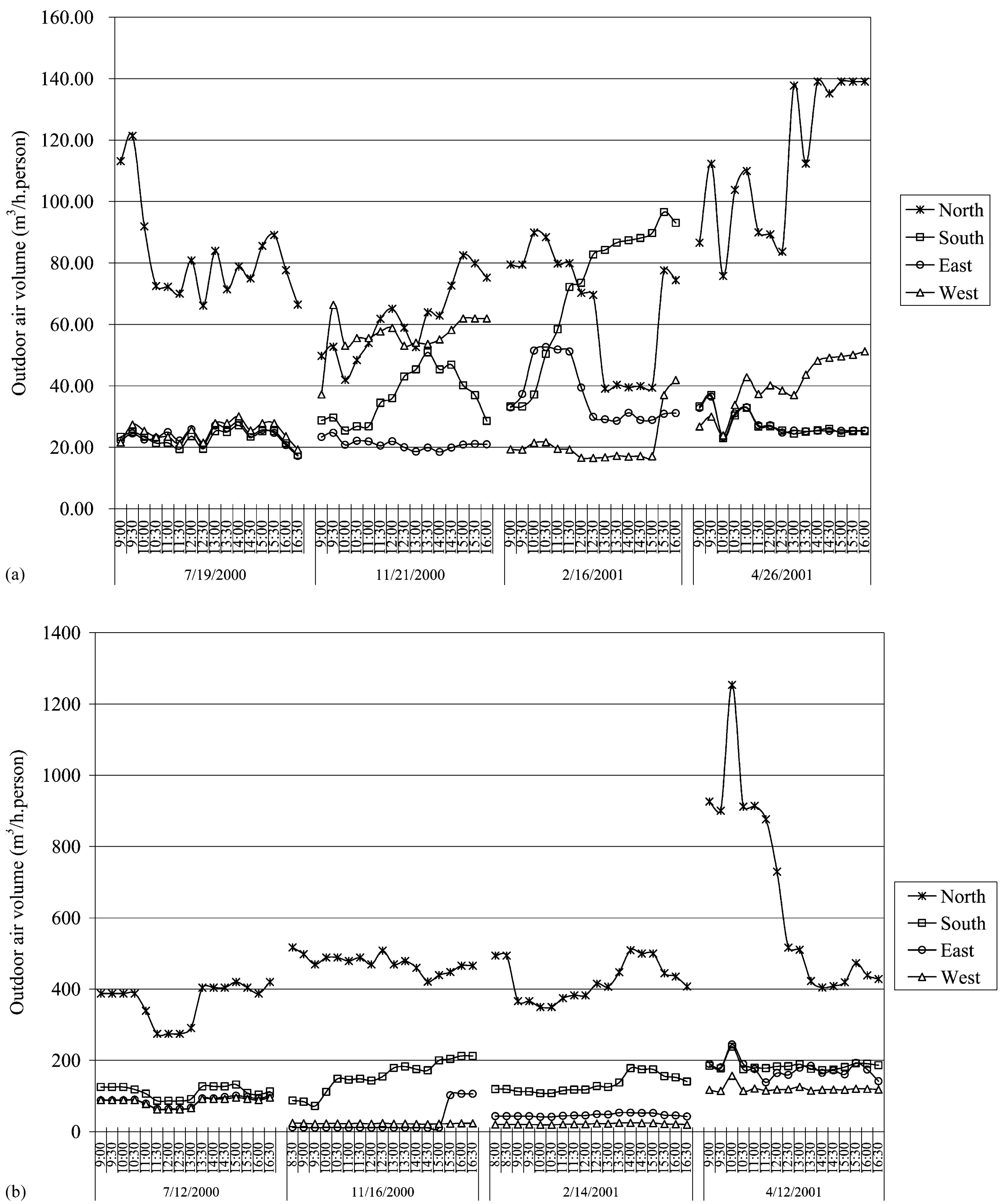
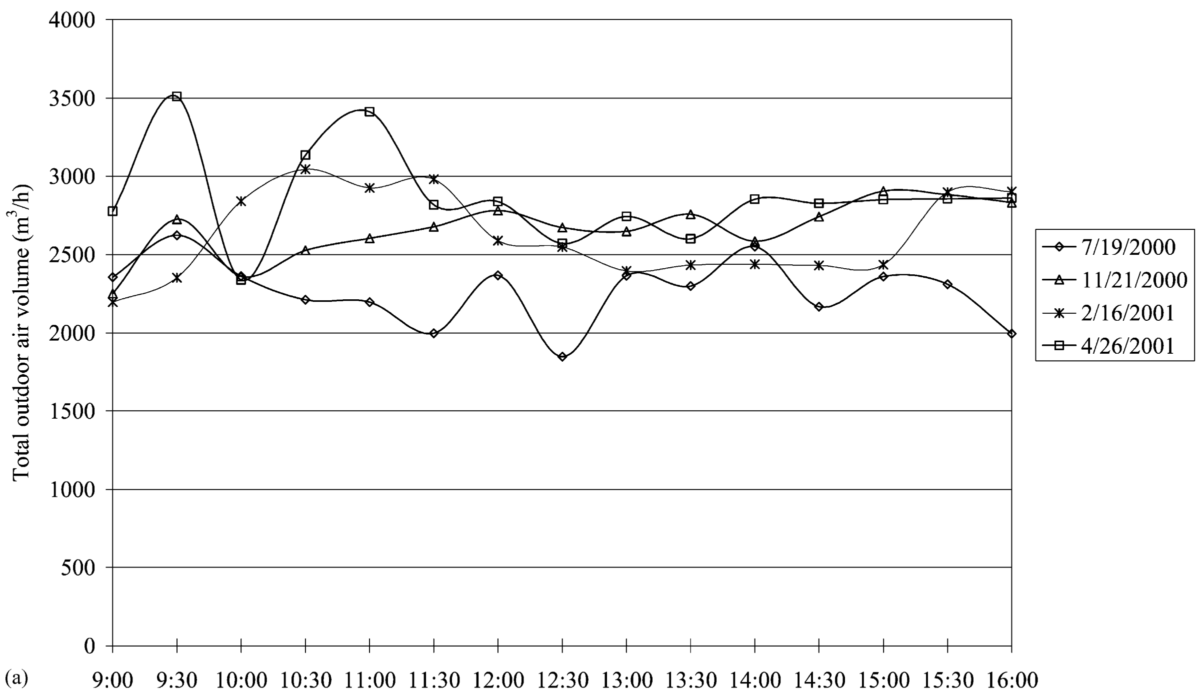


Fig. 3. (a) Outdoor airflow rate distributed to four-test spaces averaged for occupant number in Building A (measured). (b) Outdoor airflow rate distributed to four-test spaces averaged for occupant number in Building B (measured).

internal zones have to be cooled year-round and the perimeter zones have to be heated in the winter. During winter's extreme conditions, the total airflow rate of the VAV system is reduced to its minimum and the air to the perimeter zones is reheated by the reheat coils. Therefore, the VAV systems can be regarded as operating under part-load conditions during the spring, autumn and winter days. Based on the analyses above, we can conclude that the variation of outdoor airflow rate delivered to each space and the difference between outdoor airflow rates in different spaces during full-load hours are much smaller than those during part-load hours. Since the differences between T_{OA} and T_{RA} are smaller during part-load hours than full-load hours, however, the accuracy of measurements might be diminished and the resulting conclusion called into question. If we compare Fig. 2(a) and (b), we can see that the changing ranges of outdoor air-



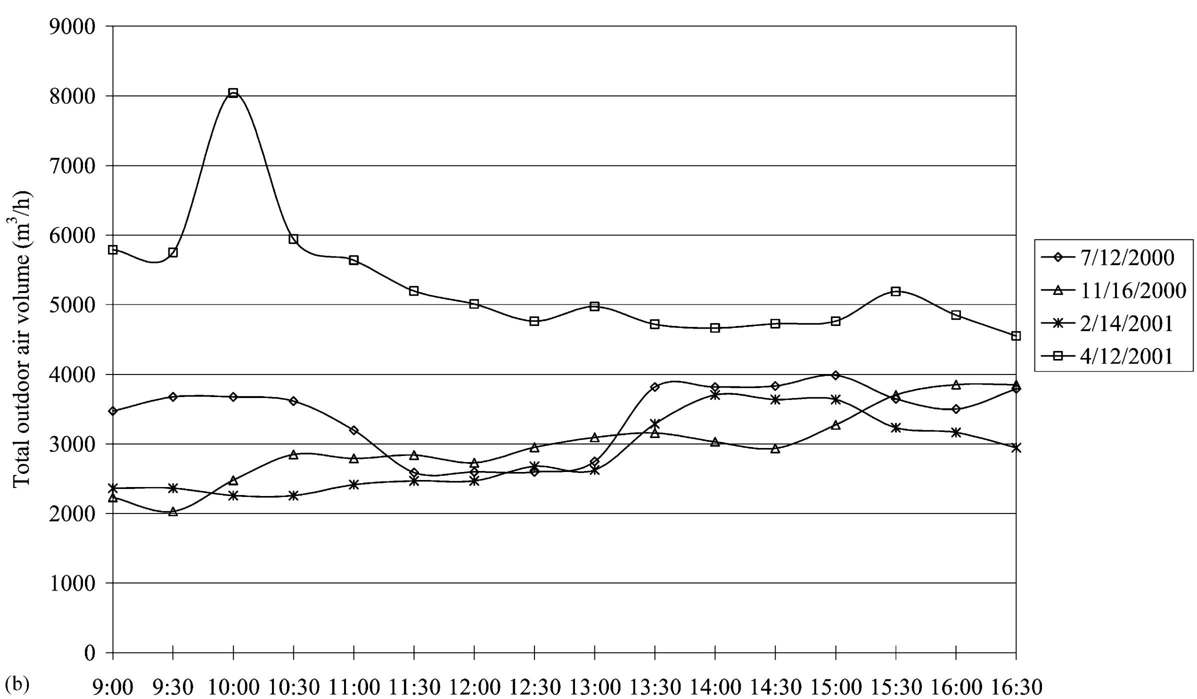


Fig. 4. (a) Total outdoor airflow rate on the 8th floor in Building A (measured). (b) Total outdoor airflow rate on the 9th floor in Building B (measured).

flow rates in Building B were much greater than those in Building A.

Fig. 3(a) shows that the outdoor airflow rate averaged for occupant number was slightly lower than 10 l/s per person ($36\,m^3$/h per person, recommended by ASHRAE Standard 62-1989 [2]) in the spaces facing south, east and west on July 19, 2000 and in the space facing east on November 21, 2000. The outdoor airflow rate averaged for occupant

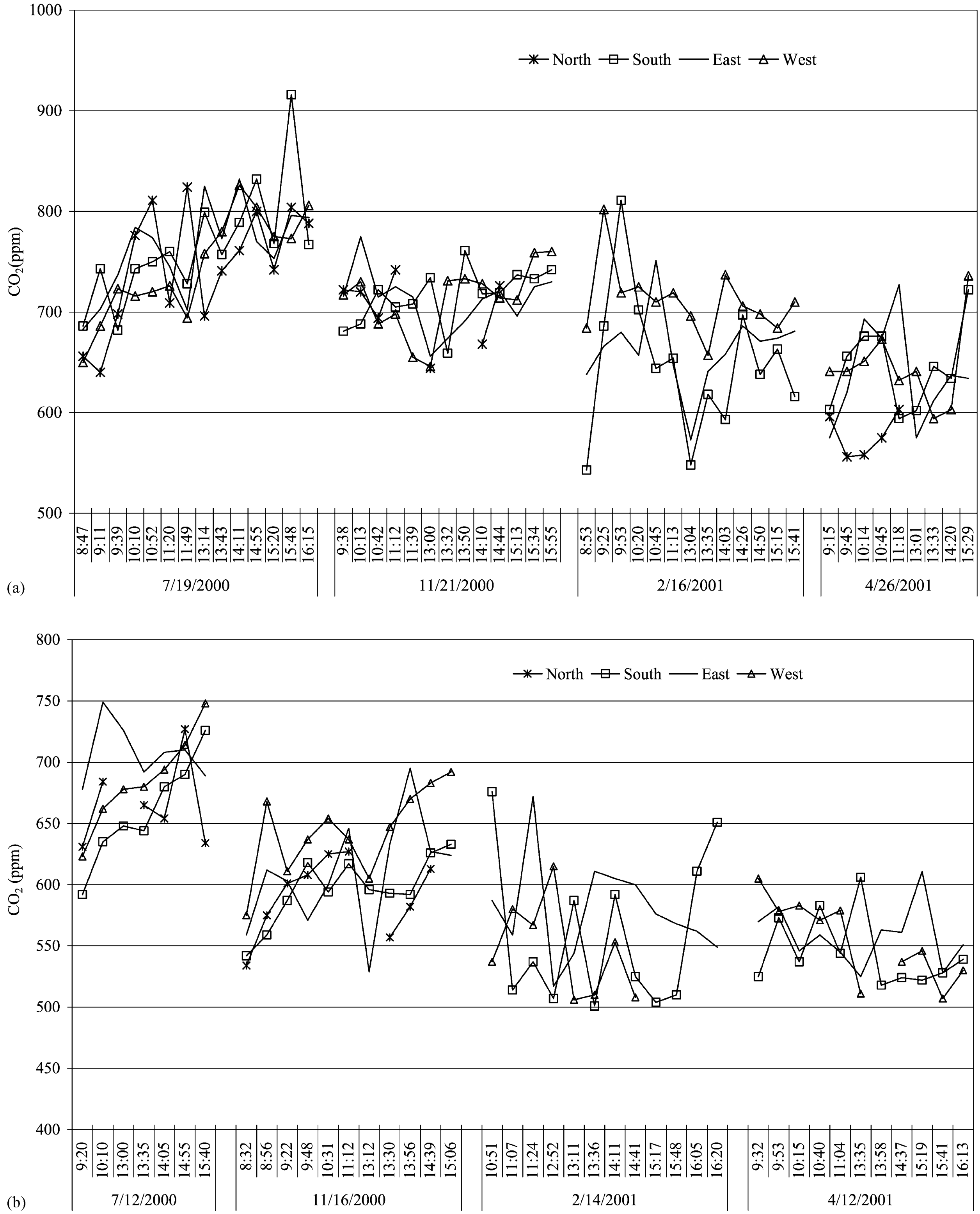


Fig. 5. (a) CO_2 concentration in Building A (measured). (b) CO_2 concentration tested in Building B (measured).

number in the space facing north was much higher than that in the other three spaces on July 19, 2000 and April 26, 2001. For Building B, as illustrated in Fig. 3(b), the outdoor airflow rate averaged for occupant number was a little lower than 10 l/s per person in the space facing west on November 16, 2000 and February 14, 2001 and in the space facing north was much higher than that in the other three spaces during all four test days.

Fig. 4(a) and (b) presents the total outdoor airflow rate for the entire office floor in the two buildings. As shown in Fig. 4(a), the total outdoor airflow rate on the 8th floor in Building A changed from 1800 to 3500 m^3/h during the test periods. As shown in Fig. 4(b), the total outdoor airflow rate on the 9th floor in Building B changed from 2000 to 8000 m^3/h during the test days, and on April 12, 2001, was much higher than on the other 3 days. The variations in total outdoor airflow rates in spring appeared greater than those in other seasons for the two buildings, a finding which could result from the lack of accuracy in measurements.

3.2. Indoor air quality

The concentrations of CO_2 and PM_{10} were measured in each test space in Building A and Building B with a TSI Q-Trak CO_2 meter and a TSI Dust-Trak aerosol meter. (See Figs. 5(a)–6(b). There are no data for the space facing north in Building A on February 16, 2001 and for the space facing north in Building B on February 14, 2001 and April 12, 2001, because measurements were not taken for some reason.) Fig. 5(a) and (b) shows that the CO_2 concentrations were lower than 1000 ppm in both Building A and Building B during the test periods, although the outdoor airflow rates averaged for occupant number in some spaces were below standard. (Refer to Fig. 3(a) and (b).) If we put Figs. 3(a), (b) and 5(a), (b) together, we cannot find a clear relationship between outdoor airflow rates per person and indoor CO_2 concentrations, either. This inconsistency might also have been caused by the measurement error for outdoor airflow rates. The PM_{10} concentrations were lower than 45 $\mu g/m^3$ in Building A during the four test days; however, the PM_{10} concentrations exceeded 150 $\mu g/m^3$ (the second class of PM_{10} specified by Chinese Ambient Air Quality Standard GB3095-1996) during the middle of the day July 12, 2000 in Building B. Many publications discussed the impact of outdoor air quality on indoor air quality [3,13–15], some showing that indoor particle concentrations depend strongly on outdoor concentrations [14,15]. Since the outdoor PM_{10} concentration on July 12, 2000 was much higher than that on the other days, we estimated that it was partly responsible for the elevated indoor PM_{10} concentrations on this day.

3.3. Energy consumption

The monthly electricity consumption of Building A and Building B in 2000 was recorded or estimated, as illustrated in broken lines in Fig. 10(a) and (b). The consumption of other types of energy, e.g. natural gas or oil, was not included. Part of the data was recorded and part was just estimated, so the accuracy of this data is questionable.

4. Simulation and calculation

Given the uncertainties of outdoor airflow rate measurement and energy consumption recording, year-round and hour-by-hour simulations were performed on Building A and Building B with DeST1.0 and DOE2.1e. For DeST1.0, a software developed by TsingHua University was used to simulate the outdoor air distribution in the spaces where site measurements were done, whereas DOE2.1e, developed by the US Department of Energy (DOE), was used to simulate the energy consumption.

4.1. Factors setting

Some factors had to be set before the simulations. These included weather-related factors, building-related factors and system-related factors. Utility rates had to be set as well. Weather-related factors included all the weather data, such as outdoor air temperature and humidity and solar radiation intensity, etc., which were contained in the weather databases of DeST1.0 and DOE-2.1e. Table 3 lists the main building-related and system-related factors as well as the utility rates for the simulations of the two buildings. Two different outdoor air control strategies: (1) fixed minimum and maximum outdoor air ratios and (2) fixed total outdoor airflow rate to each floor—were simulated for Building A and Building B, respectively, for the sake of comparison. The outdoor air ratio measured through the mixed air temperature method changed within the range of 0.1–0.2 in Building A (see Fig. 7). Therefore, in the first outdoor air control strategy, the minimum and maximum outdoor air ratios are determined as 0.1 and 0.2, respectively (see Table 3). The fixed total outdoor airflow rates to each floor in the office part of the two buildings are determined based on the design occupant numbers and ASHRAE Standard 62-1989 recommended minimum outdoor airflow rate per occupant. Since the actual occupant densities in the test spaces in the two buildings were much lower than the design value, these total outdoor airflow rates (see Table 3: 6210 m^3/h for Building A; 3326 m^3/h for Building B) are obviously more than enough for the whole floors.

4.2. Simulation results

4.2.1. Outdoor air distribution and CO_2 concentration

In the outdoor air distribution simulation, the outdoor air control strategy (1) was used in Building A and the outdoor air strategy (2) was used in Building B. Fig. 8(a) and (b) shows the hourly simulation results of the outdoor airflow rate averaged for actual average occupant number (Table 3) only in the space facing south. The outdoor airflow rates in

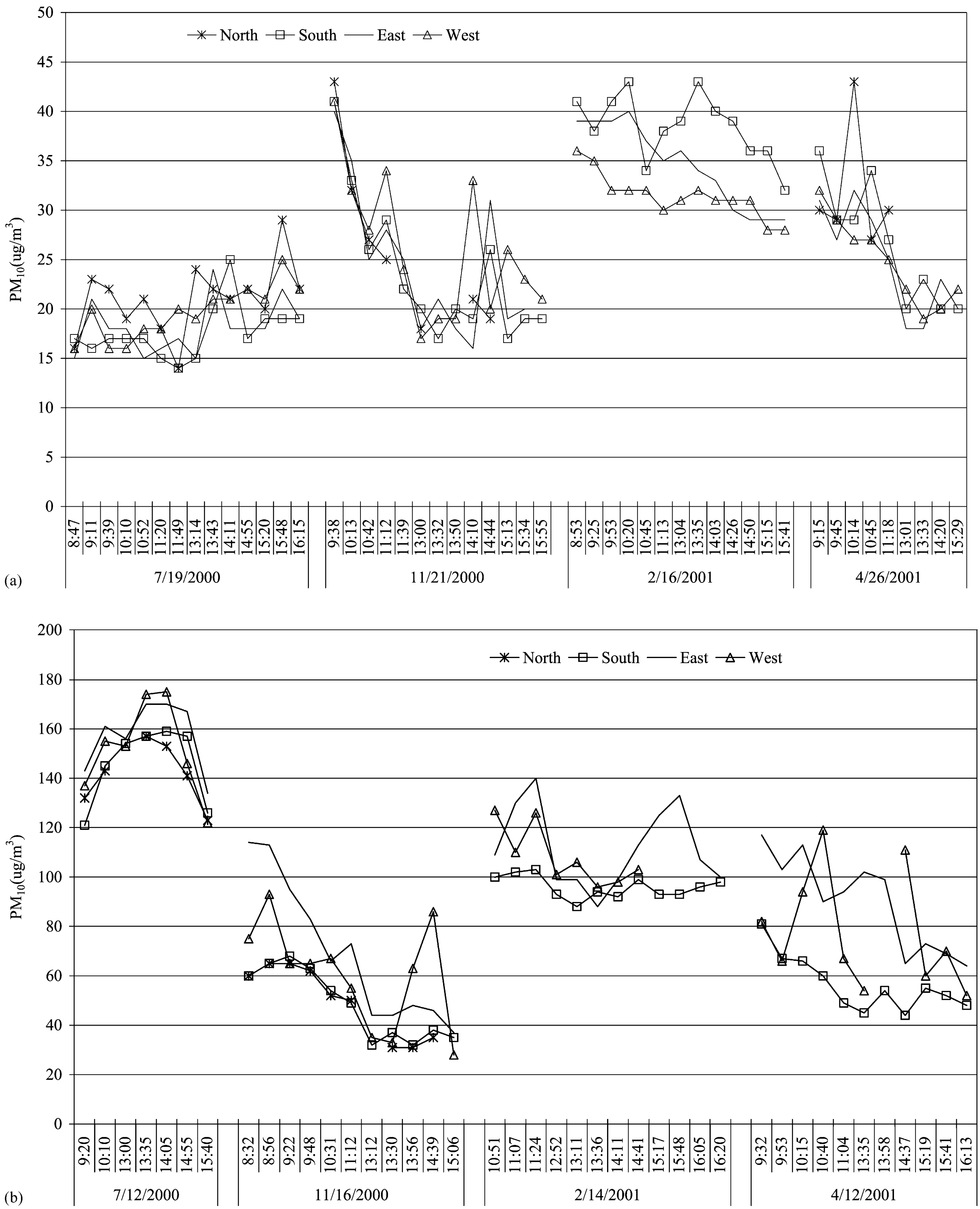


Fig. 6. (a) PM_{10} concentration tested in Building A (measured). (b) PM_{10} concentration tested in Building B (measured).

Table 3
Factors for simulation

Factors	Building A	Building B
Building-related factors		
Building envelope		
Roof	$U = 0.45\,W/m^2\,K$	$U = 1.64\,W/m^2\,K$
Wall	$U = 0.45\,W/m^2\,K$	$U = 0.45\,W/m^2\,K$
Window	$U = 3.12\,W/m^2\,K$ (summer), $U = 2.61\,W/m^2\,K$ (winter), SC = 0.36	$U = 3.24\,W/m^2\,K$; SC = 0.36
Internal loads		
People	Office: $24\,m^2$ per person[a]; hotel: $20\,m^2$ per person	$26\,m^2$ per person[a]
Lighting	Office: $20\,W/m^2$; hotel: $25\,W/m^2$	$20\,W/m^2$
Equipment	Office: $30\,W/m^2$; hotel: $25\,W/m^2$	$30\,W/m^2$
System-related factors in VAV system in office part		
Primary air temperature	$T_p = 8.8\,°C$	$T_p = 16\,°C$
Outdoor air control strategies	Fixed minimum and maximum outdoor air ratio: $R_{OA} = 0.1–0.2$ Fixed total outdoor airflow rate to each floor: $6210\,m^3/h$	Fixed minimum and maximum outdoor air ratio: $R_{OA} = 0.1–0.2$ Fixed total outdoor airflow rate to each floor: $3326\,m^3/h$
Utility rates		
Electricity		
On-peak[b]	0.889 RMB/kWh	0.895 RMB/kWh
Average[b]	0.632 RMB/kWh	0.637 RMB/kWh
Off-peak[b]	0.294 RMB/kWh	0.294 RMB/kWh
Demand charge	144000 RMB per month	93600 RMB per month
Natural gas	0.0624 RMB/MJ ($2.3\,RMB/m^3$)	0.0624 RMB/MJ ($2.3\,RMB/m^3$)

[a] Average value of actual occupant densities in four-test spaces.
[b] On-peak: 8:00–11:00 h, 18:00–21:00 h. Average: 6:00–8:00 h, 11:00–18:00 h, 21:00–22:00 h. Off-peak: 22:00–6:00 h.

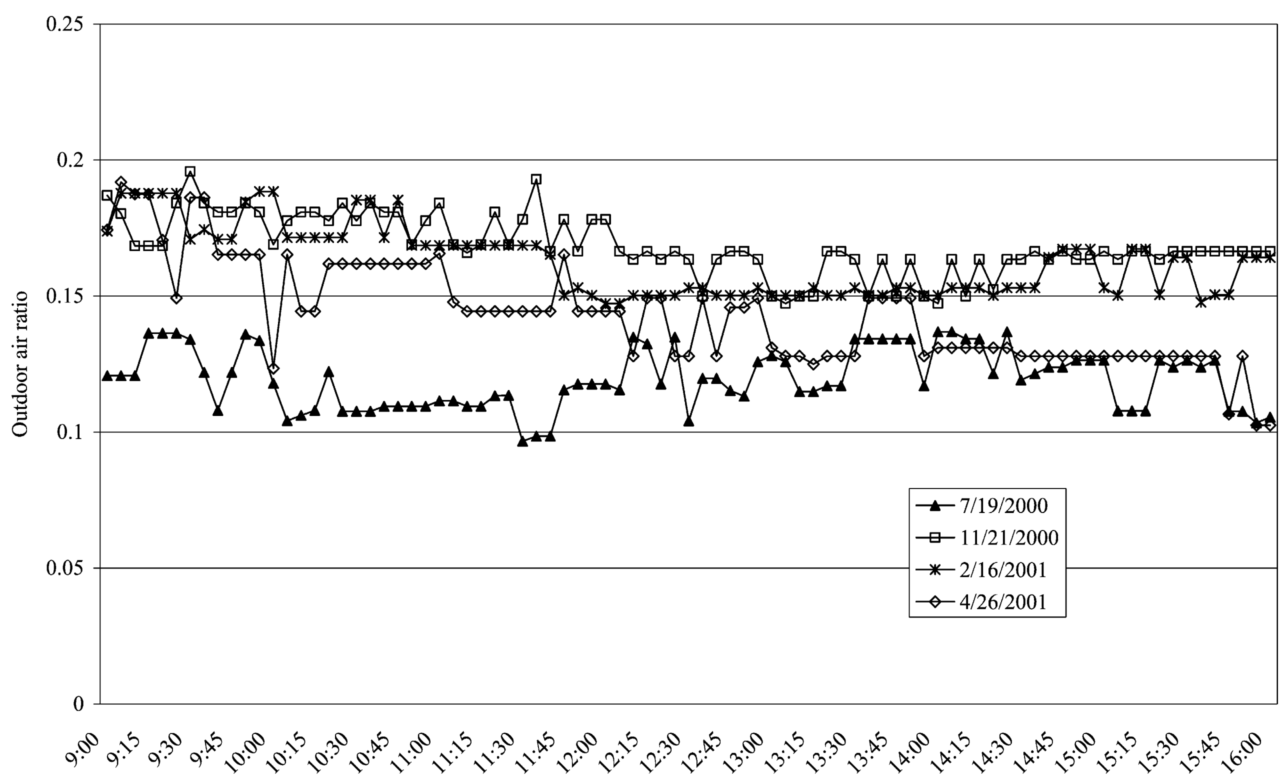


Fig. 7. Outdoor air ratios in Building A (measured).

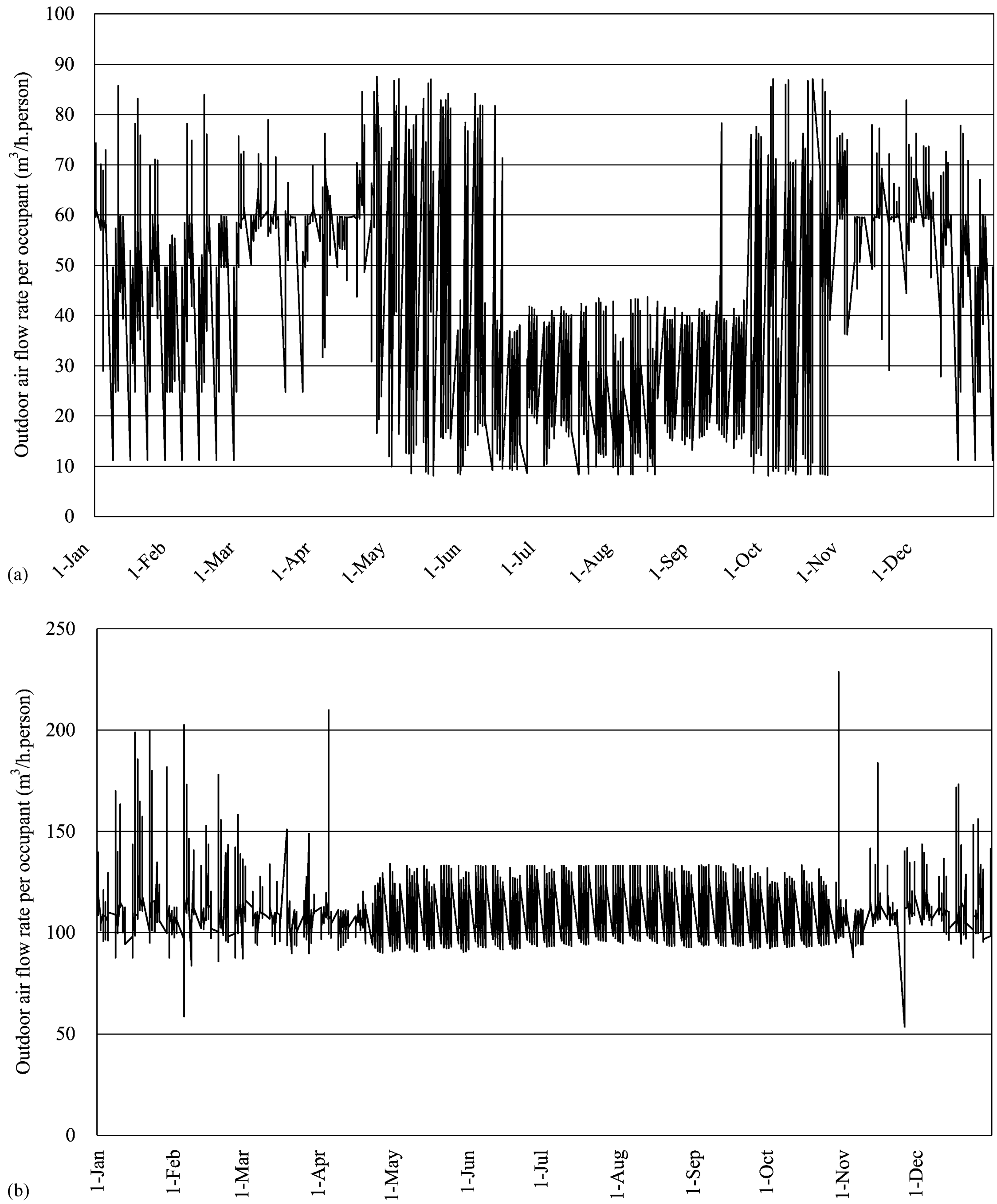


Fig. 8. (a) Outdoor airflow rate averaged for occupant number in the space facing south in Building A (simulated, outdoor air control strategy (1): $R_{OA} = 0.1$–0.2). (b) Outdoor airflow rate averaged for occupant number in the space facing south in Building B (simulated, outdoor air control strategy (2): fixed total outdoor airflow rate to each floor: 3326 m^3/h)

the other three spaces are not illustrated in these two figures, in order to make them more legible. The outdoor airflow rate per occupant in the space facing south changed from 9 to 90 m^3/h per person in Building A and changed from 50 to 230 m^3/h per person in Building B, the latter being much higher than 10 l/s per person (36 m^3/h per person).

The CO_2 concentrations under different outdoor airflow rates were calculated with the equation of ASHRAE Standard 62-1989 [2] given in Appendix D:

$$V_o = \frac{N}{C_s - C_o} \tag{2}$$

where V_o is the outdoor airflow rate per person, N the CO_2 generation rate per person, C_s the CO_2 concentration in the space, and C_o is the CO_2 concentration in outdoor air.

Eq. (2) can also be transferred into Eq. (3):

$$C_s = \frac{N}{V_o} + C_o \tag{3}$$

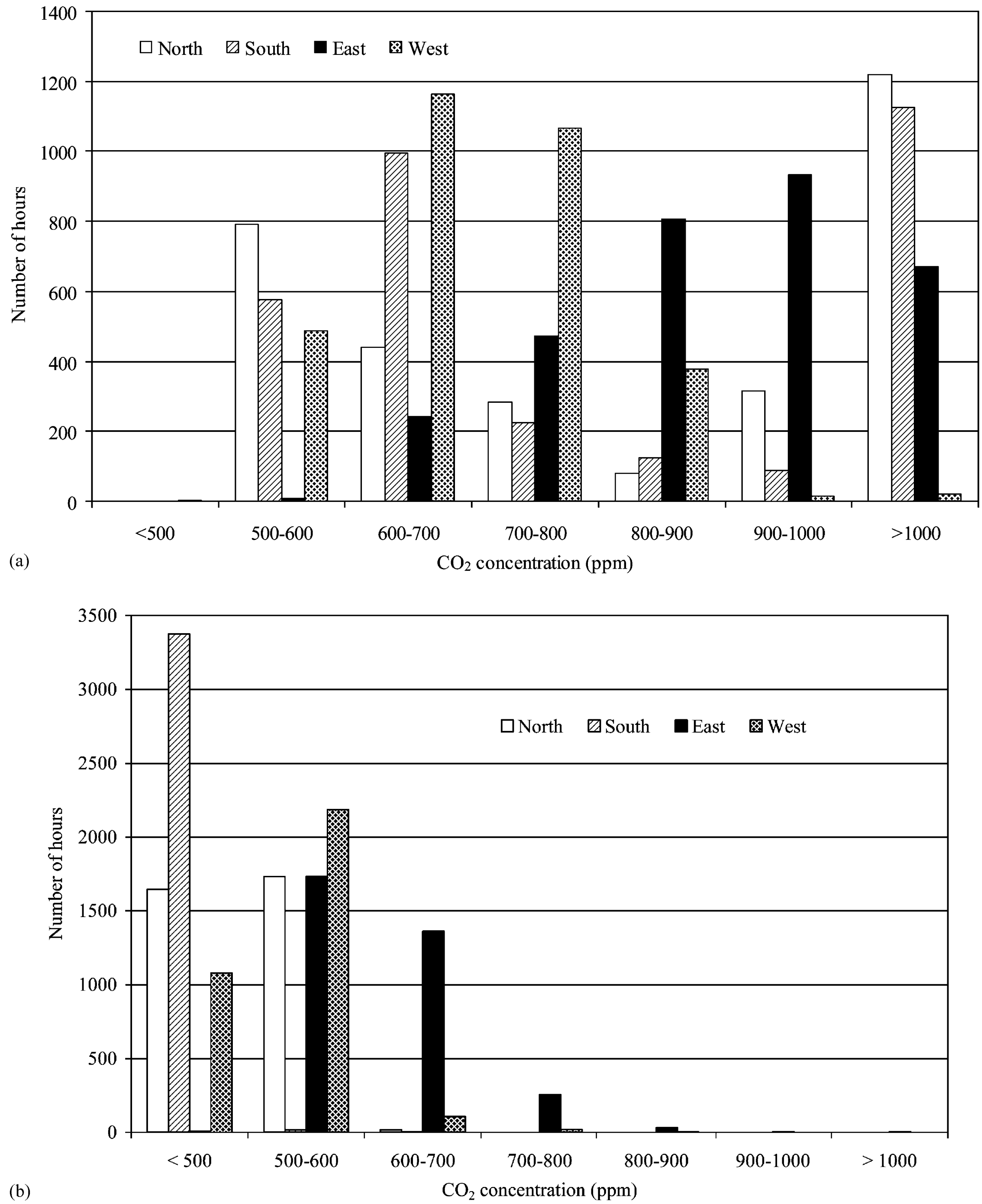


Fig. 9. (a) CO_2 concentrations in four-test spaces in Building A (simulated, outdoor air control strategy (1): $R_{OA} = 0.1$–0.2). (b) CO_2 concentrations in four testing spaces in Building B (simulated, outdoor air control strategy (2): fixed total outdoor airflow rate to each floor: 3326 m^3/h).

With Eq. (3), the space CO_2 concentration can be calculated from a specific set of outdoor air CO_2 concentration, CO_2 generation rate, and outdoor airflow rate per person. If the CO_2 generation rate is set as 0.30 l/min (1.2met) and the outdoor air CO_2 concentration is set as 300 ppm, Eq. (3) can be written as

$$C_s = \frac{18,000}{V_o\,(\mathrm{m^3/h\ per\ person})} + 300\ (\mathrm{ppm}) \tag{4}$$

Fig. 9(a) and (b) shows the frequency distribution of CO_2 concentrations in the four-test spaces each building during 3650 system operation hours (10 h per day × 365 days). As these figures show, there were more than 1000 h that CO_2 concentration exceeded 1000 ppm in the space facing north and south and more than 600 h that CO_2 concentration exceeded 1000 ppm in the space facing east in Building A during the year (Fig. 9(a)). There were few hours that CO_2

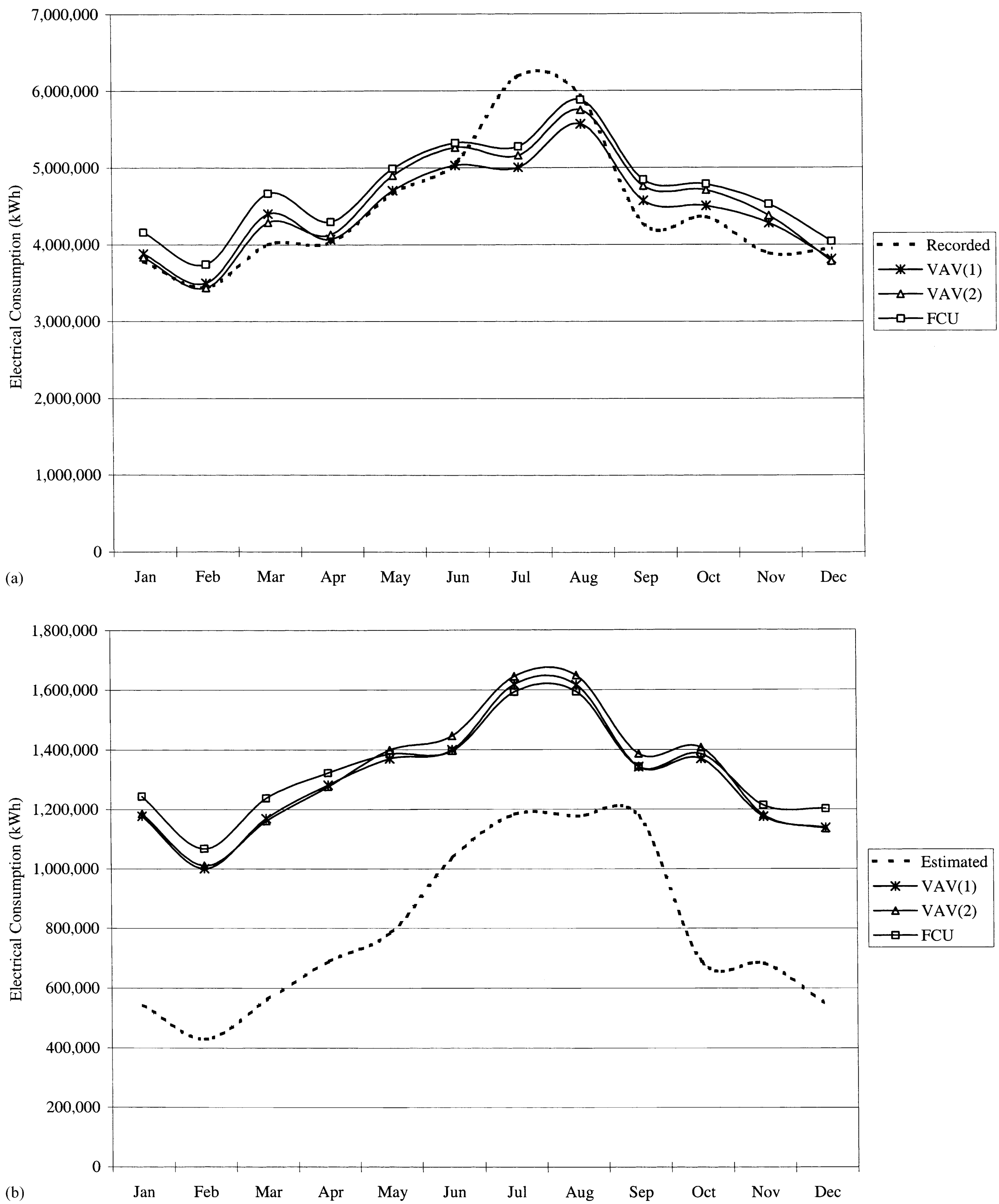


Fig. 10. (a) Monthly electrical consumption of Building A (simulated and recorded). (b) Monthly electrical consumption of Building B (simulated and estimated).

Table 4
Simulated and recorded or estimated annual energy consumption and cost of two buildings

	Energy consumption					Energy cost		
	Electrical consumption		Natural gas (MJ)	Average on total floor area[a]		Total (RMB)	Average on total floor area	
	Total	Percentage of difference		kWh/m^2	Percentage of difference		RMB/m^2	Percentage of difference
Building A								
Recorded	53579000	0.00						
VAV(1)	53338237	−0.45	10148	178	0.00	41691516	139	0.00
VAV(2)	54403165	1.54	12633	181	2.00	42642152	142	2.28
FCU	56548331	5.54	2525	188	6.01	44128928	147	5.85
Building B								
Estimated	9503142	0.00						
VAV(1)	15654441	64.73	689	209	0.00	12359836	165	0.00
VAV(2)	15875540	67.06	698	212	1.41	12521906	167	1.31
FCU	15979006	68.14	645	213	2.07	12608070	168	2.01

[a] The sum of electrical consumption and natural gas consumption in kWh averaged for total floor area.

concentration exceeded 1000 ppm in the four-test spaces in Building B (Fig. 9(b)). And there were many more hours that CO_2 concentrations exceeded 1000 ppm in Building A than in Building B. The simulation results indicated that the outdoor airflow rate averaged for occupant number varied greatly throughout the entire year, no matter which outdoor air control strategy was used. However, when the total outdoor airflow rate was maintained at a constant high level (e.g. 3326 m^3/h for 9th floor in Building B), sufficient outdoor air could be achieved for nearly all the spaces (Figs. 8(b) and 9(b)).

4.2.2. Energy consumption

The energy consumption simulation was done using the three cases for each building:

1. *VAV(1)*: use outdoor air control strategy (1) in the VAV system in the office part;
2. *VAV(2)*: use outdoor air control strategy (2) in the VAV system in the office part;
3. *FCU*: use four-pipe fan coil unit system instead of VAV system in the office part.

Table 4 shows the simulation results of the three cases and the actual recorded or estimated data. The savings of simulated data compared with recorded or estimated data and between simulated data are calculated and presented in Table 4, as well. Based on Table 4, we can do the following analyses.

- The simulated annual electricity consumption of Building A is very close to the recorded data. The difference between the simulated annual electrical consumption of VAV(1) and the recorded annual electrical consumption is only 0.45%. By contrast, the difference between the simulated and estimated annual electrical consumption of Building B is much larger (>60%). Fig. 10(a) and (b) illustrates the monthly electrical consumption of the two buildings. These two figures also show that the simulated data matches actual data much better for Building A than Building B.
- The energy consumption of VAV(2) is higher that of VAV(1) in the two buildings, which means that outdoor air control strategy (2) consumes more energy than outdoor air control strategy (1), although the former shows an indoor air quality advantage over the latter (refer to Section 4.2.1). But the differences are very small, e.g. the annual energy consumption per m^2 of VAV(2) is only 2% higher than that of VAV(1) in Building A and only 1.41% in Building B.
- The electrical consumption and cost of FCU is higher than VAV(1) and VAV(2), which proves that the VAV system has an energy advantage over the FCU system.
- The annual energy consumption and cost averaged for the total floor area in Building A are lower than those in Building B.

5. Conclusions and discussions

Site measurements and computerized simulations were performed in two high-rise buildings—Building A and Building B—in order to analyze the variation and distribution of the outdoor air in zones within each building and their impact on the IAQ, as well as the energy consumption of the VAV systems. The measured outdoor airflow rate averaged for occupant number changed within the range of 16–140 m^3/h per person in Building A and within the range of 10–1250 m^3/h per person in Building B. The measured total outdoor airflow rate changed on the 8th floor in Building A from 1800 to 3500 m^3/h and on the 9th floor in Building B from 2000 to 8000 m^3/h during the test days. The measured CO_2 concentrations changed from 540 to 920 ppm in Building A and from 500 to 750 ppm in Building B. The measured PM_{10} concentrations changed from 14 to 44 μg/m^3 in Building A and from 28 to 175 μg/m^3 in Building B. The results of site measurement on outdoor air distribution and indoor air contaminants (CO_2, PM_{10}) show very large variations in outdoor airflow rates distributed to certain zones by the VAV system as well as large differences between outdoor airflow rates between zones, factors that make it difficult to ensure that each zone meets ventilation requirements every hour. The site measurement results of CO_2 and PM_{10} concentrations did not reflect the impact of the variation of outdoor air distribution; the impact was however seen in the simulation results. During the simulation of outdoor air distribution in Building A, the percentage of outdoor air to primary air was controlled from 0.1 to 0.2, which resulted in an insufficient (substandard) outdoor airflow rate (e.g. the simulated outdoor airflow rate per occupant in the space facing south changed from 9 to 90 m^3/h per person) as well as a high concentration of CO_2 (>1000 ppm) in certain zones (the spaces facing north, south and east) for more than 15% of the system operation hours throughout the year. The outdoor air distribution simulation of Building B used a different outdoor air control strategy, which maintained the total outdoor airflow rate at a constant value (3326 m^3/h); this control strategy ensured sufficient outdoor air (e.g. the simulated outdoor airflow rate per occupant in the space facing south changed from 50 to 230 m^3/h per person) and low CO_2 concentrations in all four test zones during most of the system operation hours. For energy consumption, annual monthly data were either recorded or estimated for the two buildings. These recorded or estimated actual values were compared with the simulation results in the three cases for each building. Of the three cases, VAV(2) consumed a little more energy than VAV(1), and FCU consumed more energy than both VAV(1) and VAV(2). The simulated electrical consumption matched the actual data in Building A but not for Building B.

Although, due to possible errors in site measurement, the simulated data and the measured data cannot always be reconciled, we can, nonetheless, draw the following conclusion based on the analyses above: In a VAV system, the outdoor airflow rate distributed to each zone varies greatly, especially during part-load hours, making it difficult to ensure that the zones meet ventilation requirements every hour. When the outdoor airflow rate is lower than the minimum ventilation requirement, CO_2 concentration can exceed 1000 ppm, and IAQ problems may occur. However, use of the rational outdoor air control strategies suggested in this paper can solve the problem, although requiring more energy.

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